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ASRDI OXYGEN TECHNOLOGY SURVEY

Volume III: Heat Transfer and Fluid Dynamics—

Abstracts of Selected Technical Reports and Publications

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Volume III: Heat Transfer and Fluid Dynamics—

Abstracts of Selected Technical Reports and Publications

Edited by

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

This survey constitutes selected information from an assemblage of reports and publications on Heat Transfer and Fluid Dynamics with direct applicability to oxygen systems. For each document cited, an abstract has been prepared together with key words and a listing of most important references found in the document. Additionally, an Author Index, a Subject Index, and a Key Word Index have been provided to simplify the retrieval of specific information from this work. In each subject area -- e.g., Boiling Heat Transfer -- the individual citations are listed alphabetically by first author, with review papers dually noted under the appropriate subject category and under Review Papers.

Of the documents reviewed and evaluated for inclusion in this publication, coverage of existing information directly concerned with oxygen was given primary emphasis. However, work not specifically oxygen-designated but considered applicable to oxygen by the reviewer -- e.g., a two-phase friction factor correlation derived from nitrogen experiments -- is occasionally given where no actual oxygen data exists, as an aid to the reader.

KEY WORDS: Boiling heat transfer; bubble dynamics; cavitation; condensing heat transfer; correlations; cryogenic fluid safety; fluid dynamics; fluid transfer; heat transfer; heat transfer equipment; liquid helium; liquid hydrogen; liquid nitrogen;

17. KEY WORDS (Alphabetical order, separated by semicolons)
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PREFACE

This publication is part of an oxygen safety review in progress by the NASA Aerospace Safety Research and Data Institute (ASRDI). The objectives of the review include:

1. Recommendations to improve NASA oxygen handling practices by comparing NASA and contractor oxygen systems including the design, inspection, operation, maintenance, and emergency procedures.
2. Assessment of the vulnerability to failure of oxygen equipment from a variety of sources so that hazards may be defined and remedial measures formulated.
3. Contributions to safe oxygen handling techniques through research.
4. Formulation of criteria and standards on all aspects of oxygen handling, storage, and disposal.

This Special Publication is composed of information obtained from selected publications on Heat Transfer and Fluid Flow. Documents reviewed and abstracted summarize the pertinent information on oxygen and other cryogenic fluids for which the data may be considered applicable.

Problem areas are indicated in the description of currently accepted models and hypotheses for mechanisms. Many of the design methods and/or equations available are given a critical evaluation in this publication pointing out, to both the scientific and technical communities, areas requiring increased studies. This work was initiated by I. Irving Pinkel, former Director of ASRDI.

Frank E. Belles, Director
Aerospace Safety Research and Data Institute
National Aeronautics and Space Administration

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INTRODUCTION

This survey constitutes selected information from an assemblage of reports and publications on Heat Transfer and Fluid Dynamics with direct applicability to oxygen systems. For each document cited, an abstract has been prepared together with key words and a listing of most important references found in the document. Additionally, an Author Index, a Subject Index, and a Key Word Index have been provided to simplify the retrieval of specific information from this work. In each subject area — e.g., Boiling Heat Transfer — the individual citations are listed alphabetically by first author, with review papers dually noted under the appropriate subject category and under Review Papers.

Of the documents reviewed and evaluated for inclusion in this publication, coverage of existing information directly concerned with oxygen was given primary emphasis. However, work not specifically oxygen-designated but considered applicable to oxygen by the reviewer — e.g., a two-phase friction factor correlation derived from nitrogen experiments — is occasionally given where no actual oxygen data exist, as an aid to the reader.

Identification of a manufacturer's product in this publication in no way implies a recommendation or endorsement by the National Bureau of Standards or by the National Aeronautics and Space Administration.

HEAT TRANSFER

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BOILING HEAT TRANSFER FOR OXYGEN, NITROGEN, HYDROGEN AND HELIUM

Brentari, E. G., Giarratano, P. G., and Smith, R. V. (Cryogenics Division, National Bureau of Standards, Boulder, Colo.)

Nat. Bur. Stand. (U. S.) Tech. Note 317 (Sep 1965)

This report was written mainly for the benefit of designers. Experimental data to 1965 on pool boiling (nucleate and film) and on forced convective boiling are compared with correlations for liquids oxygen, nitrogen, hydrogen, and helium. For pool boiling, the correlations of Kutateladze for the nucleate heat flux as a function of driving temperature difference, and the peak nucleate boiling flux, were selected as most representative of the available data. For the film boiling regime the correlation of Breen and Westwater was chosen; the correlation of Lienhard and Wong was chosen for the minimum film heat flux. These correlations were then used to generate curves of heat flux vs. driving temperature difference for each liquid at selected pressures and heater diameters.

For forced convective boiling a statistical method was used to compare the predictive reliability of several common correlations using available data on hydrogen. The result of the comparison indicates that none of the proposed predictive methods fall in a respectable range of reliability and, furthermore, for design purposes, the simpler correlations seem to compare favorably with the more complex approaches.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 16.)

CRYOGENIC HEAT TRANSFER

Clark, J. A. (University of Michigan, Ann Arbor, Michigan, Department of Mechanical Engineering)

Advan. Heat Transfer 5, 325-517 (1968)

This is an extensive and useful review of the subject through 1967 with 278 references. The general subject headings are: Conduction Heat Transfer; Forced-Convection Processes; Natural Convection Processes; Pressurized-Discharge Processes for Cryogens; Stratification in Cryogenic Vessels; Multiphase Processes; Radiation; Helium II.

Under Conduction Heat Transfer the author concentrates first on the common cryogenic problem of an extensive variation in physical properties over the temperature range of interest, giving transformations which reduce or eliminate the non-linearity of the conduction equation. The subject of low-temperature thermal insulation is discussed briefly and a discussion of interfacial phenomena is included under this heading viewed as essentially a conduction phenomenon.

Heat transfer correlations are discussed under Forced Convection Processes where again large property variation is the major non-classical problem of cryogenic interest. In Natural Convection Processes the usual classical expressions of the form $Nu = C(Gr \cdot Pr)^n$ are found to be suitable for cryogens, where Nu = Nusselt No., Gr = Grashof No., Pr = Prandtl No., C and n are the empirical constants. One new aspect added to this subject by the field of cryogenics is the testing of these relationships over wide gravity variations as necessitated by aerospace applications.

The author himself has worked extensively in the fields of Pressurization and Stratification. He discusses both a closed form analytical solution for an idealized pressurization process and a flexible computer model which is capable of good representation of pressurization parameters. Comparisons with experimental data are shown. Under Stratification, the boundary layer model is discussed along with scaling laws derived from it. A more exact approach is the numerical solution of the conservation equations, in which the author has been engaged with some success in producing the detailed streamlines and isotherms, as well as total system parameters like pressure-rise rate.

The section on Multiphase Processes is largely concerned with the voluminous literature on boiling heat transfer to cryogens including pool boiling (nucleate, film and transition regions, maximum and minimum heat fluxes and correlations) and forced convection boiling. Special attention is given to the influence of both increased and decreased gravity on pool boiling. Also considered under Multiphase Processes is injection cooling and frost formation. Unfortunately the subjects of condensation and freezing are not considered.

The section on Radiation is limited to the thermal radiation properties of metal surfaces and the effects of cryodeposits of water and carbon dioxide. Finally, many of the interesting heat transfer properties of helium II are discussed, including internal convection, Kapitza resistance, maximum heat flux, film boiling and turbulent convection.

CRYOGENIC HEAT TRANSFER
Clark, J. A.

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Key words: Absorption; boiling heat transfer; boundary layer mode; bubble chamber; carbon dioxide; condensing heat transfer; convection; convection heat transfer; cryodeposit; emissivity; evaporation; film boiling; forced convection; frost formation; Grashof number; heat leaks; heat transfer rates; helium II; insulation; interfacial phenomena; Kapitza resistance; leakage and spills; liquid-vapor interface; liquid helium; liquid hydrogen; liquid nitrogen; liquid oxygen; metals; missiles and rockets; multilayer insulation; natural convection; nuclear powered vehicles; Nusselt number; polyester; pool boiling; Prandtl number; pressurization; propellant tanks; radiation heat transfer; scaling laws; spacecraft; spacecraft tankage; storage; stratification; supercritical heat transfer; superfluid helium; superinsulation; thermal conductivity; transportation; water.

A REVIEW OF PRESSURIZATION, STRATIFICATION AND INTERFACIAL PHENOMENA
Clark, J. A. (Michigan University, Ann Arbor, Mich.)
Advan. Cryog. Eng. 10, (Sects. M-U) 259-83 (1965)

These phenomena (pressurization, stratification and interfacial processes) are closely interrelated, and successfully predicting their behavior is very important to propellant tank design and pumping and transfer systems. This review is quite thorough, with 69 references cited. The paper is primarily concerned with analytical approaches to the problem.

Analytical approaches may be divided into the following categories —

For processes and properties:

1. Lumped systems - dealing with mean property values of the gas and wall as a function of time.

2. Distributed systems - in which temperature, density and velocity are determined as a function of space and time.

For the solution to analytical expressions:

1. Closed form - where proper assumptions are made to formulate expressions allowing this type of solution.

2. Numerical - where step-wise integration is performed essentially without the simplifying solutions of the closed form (above).

The author states that experience to date allows the following conclusions: Minimum gas residual is achieved by maximizing inlet gas temperature, minimizing its pressure, and selecting a pressurant with low molecular weight and high heat capacity. Interface heat transfer is negligible with respect to wall heat transfer.

Stratification can result from pressurization and from the distribution of heat transferred to the cryogen during storage. When energy is added at a vertical wall, there is an upward flow of low density fluid near the wall; if, as for the usual case, there are no forces to provide mixing or downward flow of the low density layer into the higher density region, this low density fluid forms a warmer, low density layer at the top of the stored cryogen. A number of predictive methods have been proposed differing rather widely in approach. Satisfactory agreement with experiments has been achieved in some cases but insufficient data are available to judge the relative merit of the various approaches.

Interfacial phenomena, or the transport of energy and mass (vaporization or condensation) at the interface, plays an important part in the pressurization and stratification processes. Studies to date have achieved some success in predicting the interface process behavior but are not completely conclusive. They do indicate that a) the interface temperature is essentially the saturation temperature for the system pressure, b) during self-pressurization (from heat transfer at the walls), interfacial evaporation occurs and the system pressure is governed by the vapor pressure characteristics of the phases at the interfacial temperature.

Although some guidance for designers has been provided by the works summarized here, a reliable solution required for optimal design has not been achieved for any of the phenomena discussed. An impressive list of unresolved problems is included.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A MORE DETAILED ABSTRACT, SEE PAGE 41.)

SURVEY OF HEAT TRANSFER TO NEAR-CRITICAL FLUIDS
Hendricks, R. C., Simoneau, R. J., and Smith, R. V. (NASA, Lewis Research Center, Cleveland, Ohio)
NASA Tech. Note D-5886 (Nov 1970); also Advan. Cryog. Eng. 15, 197-237 (1970)

The purpose of this report is to collect and examine information on this topic from a designer's viewpoint. Heat transfer regions are initially defined on the basis of fluid properties. The regions are:

Gas-fluid
Liquids
Two-phase
Near-critical.

After a very brief summary of the first three regions, the remainder of the report is devoted to the near-critical region. Fluid properties are discussed, followed by a detailed treatment of various heat transfer topics:

Free convection
Loops-natural convection process
Forced convection process
Geometric effects
Theoretical considerations
Oscillations
Choking phenomenon
Zero gravity.

The forced convection study using oxygen reported by Powell (1957) indicates oxygen behavior to be similar to that of other fluids. 217 references are cited (also arranged with respect to subject matter) and each topic is covered quite thoroughly.

In the near-critical region, no heat transfer correlation was found to be satisfactory to a designer's needs. Property and subsequent heat transfer process changes are frequent and very sensitive to changes in the heat transfer system. These may result in:

Wall temperature excursions (spikes)
Oscillations
Large momentum pressure drops
Failure of conventional correlations.

Recommendations are made in a framework of the current state-of-the-art.

Important references:

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SURVEY OF HEAT TRANSFER TO NEAR-CRITICAL FLUIDS
Hendricks, R. C., Simoneau, R. J., and Smith, R. V.

Important references: (continued)

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Key words: Ammonia; carbon dioxide; convection heat transfer; critical (choking) two-phase flow; critical flow; critical region; fluid oscillations; forced convection; free convection; freon 12; freon 114; geometry effect; helium; hydrogen; kerosene; methane; missiles and rockets; natural convection; nitrogen; oxygen; pressure drop; propane; thermal-acoustic oscillations; thermal conductivity; thermal oscillations; tubes; two-phase; viscosity; water; zero gravity.

A REVIEW ON FILM BOILING
Hsu, Y. Y. (National Aeronautics and Space Administration, Cleveland, Ohio, Lewis Research Center)
Advan. Cryog. Eng. 17, 361-81 (1972)

The author presents a very thorough review of film boiling with considerable emphasis on the analytical (theoretical) approach to the subject. The treatment is general, and the discussion is probably as applicable to oxygen as to any other fluid. [However, one reference is cited which suggests different behavior for nitrogen.]

Subjects covered are: 1) boiling of drops and puddles; 2) pool boiling for various geometrics; 3) forced convection film boiling inside channels and tubes. The report offers a good source of film boiling references. Recommendations are made for further work.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 20.)

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BOILING HEAT TRANSFER FOR CRYOGENS
Seader, J. D., Miller, W. S., and Kalvinskas, L. A. (Rocketdyne, Canoga Park, Calif.) National Aeronautics and Space Administration, Huntsville, Ala., Contractor Report No. CR-243 (Jun 1965)

This is a very comprehensive review with 353 references, including graphically presented data for fluid properties required in the proposed expressions to describe the boiling phenomenon. Specific subjects treated are pool, forced and natural convection boiling, geometry and other pertinent conditions such as surface effects, vortices, gravitational effects, electrical fields and agitation for both experimental and theoretical studies.

Particularly useful tables are presented to summarize theoretical approaches to nucleate boiling, nucleate boiling maximum heat flux, and film boiling minimum heat flux.

Experimental and analytical results are compared and those analytical results which fall within the spread of the experimental data indicated. This information serves as a useful guide to designers. Recommendations emphasize the need for more experimental data to determine the apparent disagreements between the rather meager experimental data reported to date for both pool and forced convection boiling. Studies of the surface and geometry effects are also strongly recommended.

This is a very thorough and detailed report and is a valuable reference for any studies involving the boiling of cryogenic fluids.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 25.)

CRYOGENIC APPLICATION OF BASIC SCIENCES
Smith, R. V., and Gosman, A. L. (National Bureau of Standards, Boulder, Colo., Cryogenics Division)
Technical Manual of Oxygen/Nitrogen Cryogenic Systems, Chapter 6, NAVAIR 06-30-501, Schmidt, A. F. ed. (Mar 1971)

The chapter is intended to serve as an introduction and guide to provide a background for operational (Naval) personnel who have had little previous experience or training in engineering or in cryogenics. The three major subject divisions are thermodynamics, fluid mechanics, and heat transfer with appropriate emphasis on heat transfer. There are approximately thirty example problems, completely worked, which are concerned with oxygen or nitrogen as the cryogenic fluid.

The thermodynamics section defines terms, discusses fluid property behavior, and introduces the First Law (conservation of energy). This information allows the calculation of a wide group of energy-related problems (where time is not a critical factor) such as pressure build-up in storage, fluid property determination (pressure, volume, temperature), and cryogen quantities required for cooldown of equipment.

The fluid mechanics section is primarily concerned with pressure drop in transfer lines and in fluid metering.

The heat transfer section introduces the basic equations and considers conduction, convection and radiation.

Many example problems in heat transfer are included, such as heat leak in dewars and heat transfer in flowing fluids — both by natural and forced convection.

Key words: Bibliography; conduction heat transfer; convection heat transfer; fluid dynamics; fluid mechanics; gaseous nitrogen; gaseous oxygen; liquid nitrogen; liquid oxygen; radiation heat transfer; thermodynamics.

STABLE FILM BOILING OF LIQUID OXYGEN OUTSIDE SINGLE HORIZONTAL TUBES AND WIRES

Banchero, J. T., Barker, G. E., and Boll, R. H. (Michigan University, Ann Arbor, Michigan)

Chem. Eng. Progr. Symp. Ser. 51, No. 17, 21-31 (1955)

In this investigation, film boiling heat transfer of liquid oxygen on horizontal wires and tubes was studied in an attempt to establish the diameter and pressure dependence. Pressures were varied from 5 to 500 lb/in^2 and diameters ranged from 0.025 to 0.750 in. It was found that Bromley's equation fitted the experimental data for a restricted range of tube diameters (0.069 - 0.127 in). An empirical fit of the data for all tube diameters studied was obtained by replacing $D^{-0.25}$ by $[1/D + C]$, where D is the tube diameter and C is an empirical constant. For the range of pressures investigated, and for a given diameter, Bromley's equation was found to predict the results within experimental error. All experimental results could be predicted with the simple empirical relation

$$h = a_2 [1/D + C]\ P^{0.25}$$

where

h	=	heat transfer coefficient (Btu/hr ft^2 °F)
a_2	=	constant with slight dependence on temperature difference (Btu)(in)/(hr)(ft^2)(°F)(lb/in^2)$^{0.25}$
C	=	36.5 in^{-1}
P	=	pressure (lb/in^2).

Values of a_2 are given, ranging between 0.441 and 0.302 for temperature differences between 100 and 500°F, respectively. This equation should not, of course, be used outside the quoted range of the experimental data.

Further observations indicated that the lower limit of stable film boiling for oxygen occurs at a temperature difference in the vicinity of 100°F at atmospheric pressure.

Important references:

1. Bromley, L. A., Chem. Eng. Progr. 46, 221 (1950).

See also:

1. Breen, B. P. and Westwater, J. W., Chem. Eng. Progr. 58, 67-72 (1962).

2. Brentari, E. G., Giarratano, P. J. and Smith, R. V., Nat. Bur. Stand. (U. S.) Tech. Note 317 (Sep 1965).

Key words: Boiling heat transfer; copper; equations; heat transfer; heat transfer coefficients; horizontal; liquid oxygen; outside tubes; platinum; stainless steel; storage; transportation; tubing; wires.

CONTRIBUTION TO THE PROBLEM OF HEAT TRANSFER IN LOW-BOILING LIQUIDS
Bewilogua, L., and Knöner, R., (Universität, Dresden, East Germany)
J. Amer. Chem. Soc. 90, 3086-7 (1968)

Curves of heat flux density versus temperature difference are presented for a stainless steel-jacketed lead cylinder with vertical axis immersed in liquids hydrogen, neon, oxygen, nitrogen, and argon. The main value of the paper is in data for oxygen which show the enhancement of the peak nucleate boiling heat flux when the cylinder was coated with various thicknesses of varnish. In addition to this enhancement, the whole nucleate boiling range is thereby extended to higher temperature differences.

Key words: Boiling heat transfer; coating; cylinder; film boiling; heat flux density; insulation; liquid argon; liquid hydrogen; liquid neon; liquid nitrogen; liquid oxygen; nucleate boiling; outside tubes; pool boiling; surface effects; varnish.

IMPROVEMENT OF HEAT EXCHANGE IN BOILING LIQUIDS BY APPLICATION OF AN ALTERNATING ELECTRIC FIELD

Bochirol, L., Bonjour, E., and Weil, L. (Centre d'Etudes Nucleaires de Grenoble, France)

Bull. Inst. Int. Froid Annexe, 251-6 (1960)

Boiling heat transfer is improved by the application of an alternating electric field perpendicular to the horizontal heater wire. With electric fields up to 165 kV/cm, an increase of the heat transfer coefficient in the free convection region by a factor of 2.5 to 3 is obtained with liquids nitrogen, argon, and oxygen. In addition, the peak nucleate boiling flux is increased by a factor of about 2.5 (without change in temperature difference), and the film boiling coefficients are increased by a factor of about 1.5.

Important references:

1. Ashmann, G. and Kronig, R., Appl. Sci. Res. A2, 235 (1950) and Erratum 3, 83 (1951).

Key words: AC electric fields; boiling heat transfer; convection heat transfer; field strength; film boiling; free convection; heat transfer coefficient; horizontal; liquid argon; liquid nitrogen; liquid oxygen; nucleate boiling; platinum; storage; transportation; wires.

BOILING HEAT TRANSFER FOR OXYGEN, NITROGEN, HYDROGEN AND HELIUM
Brentari, E. G., Giarratano, P. G., and Smith, R. V. (Cryogenics Division, National Bureau of Standards, Boulder, Colorado)
Nat. Bur. Stand. (U.S.) Tech. Note 317 (Sep 1965)

This report was written mainly for the benefit of designers. Experimental data to 1965 on pool boiling (nucleate and film) and on forced convective boiling are compared with correlations for liquids oxygen, nitrogen, hydrogen, and helium. For pool boiling, the correlations of Kutateladze for the nucleate heat flux as a function of driving temperature difference, and the peak nucleate boiling flux, were selected as most representative of the available data. For the film boiling regime the correlation of Breen and Westwater was chosen; the correlation of Lienhard and Wong was chosen for the minimum film heat flux. These correlations were then used to generate curves of heat flux vs. driving temperature difference for each liquid at selected pressures and heater diameters.

For forced convective boiling a statistical method was used to compare the predictive reliability of several common correlations using available data on hydrogen. The result of the comparison indicates that none of the proposed predictive methods fall in a respectable range of reliability and, furthermore, for design purposes, the simpler correlations seem to compare favorably with the more complex approaches.

Important references:

1. Kutateladze, S. S., State Sci. and Tech. Pub. of Lit. on Machinery, Moscow (AEC translation 3770, Tech. Info. Service, Oak Ridge, Tennessee).
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4. Hendricks, R. C., Graham, R. W., Hsu, Y. Y., and Friedman, R., NASA Tech. Note D-765(1961).
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Key words: Boiling heat transfer; density; enthalpy; film boiling; forced convection; gaseous; geometry effects; gravity effects; helium; helium 4; horizontal; hydrogen; liquid helium; liquid hydrogen; liquid nitrogen; liquid oxygen; nitrogen; nucleate boiling; parahydrogen; plates; pool boiling; saturated liquids; saturation properties; size effects; specific heat at constant pressure; specific volume; storage; subcooled liquids; surface effects; surface tension; thermal conductivity; transportation; tubing; vapor pressure; vertical; viscosity.

PREDICTION OF BURN-OUT POWER WITH FREON UP TO THE CRITICAL PRESSURE

Cumo, M., Ferrari, G., and Urbani, G.
Comitato Nazionale per l'Energia Nucleare, Casaccia (Italy),
Centro di Studi Nucleari Lab. Rept., 14 pp

This paper reports the experimental use of freon to test burn-out (wet-to-dry wall transition) correlations, particularly over a wide range of fluid conditions. The best correlation was the CISE correlation reported by Silvestri et al (ref. 4). However, this correlation did not predict very well above the reduced fluid pressure (p/p_{cr}) of 0. 55, so an additional correlative pressure term was added for that case.

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1. Clerici, G. C., Garriba, S., Sala, R. and Tozzi, A., Euratom Report No. EUR 3300. e (1966).

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Key words: Burnout; equation; freon 12; heat leaks; liquid oxygen; mathematical analysis; quality; size effects; storage; transportation; two-phase flow; water.

HEAT TRANSFER FROM OXYGEN BOILING IN TUBES
Elukhin, N. K., and Vishnev, I. P.
Kislorod 12, No. 4, 5-15 (1959)

Experimental studies on heat exchange performed with oxygen boiling in vertical tubes of different size and over a wide range of heat loads have shown that the ratio of the tube length to the diameter has a substantial effect on heat exchange, at $L/d > 80$. On the basis of a great number of experimental data the authors suggest a formula for determining the heat transfer from oxygen boiling in tubes at natural conditions of circulation. It was experimentally found that hysteresis occurred in the oxygen boiling process.

Key words: Air separation plants; boiling heat transfer; convection; equations; heat transfer equipment; heat transfer rates; hysteresis; liquid oxygen; loads; nucleate boiling; transportation; tubes; storage; vertical.

SIMILARITY AND CURVATURE EFFECTS IN POOL FILM BOILING

Hendricks, R. C., and Baumeister, K. J. (National Aeronautics and Space Administration, Cleveland, Ohio, Lewis Research Center)

Paper presented at 4th Inter. Heat Transfer Conf., Versailles, Sept. 1970

This paper treats the effects of film boiling on large and small spheres. Experimental data are presented for cooldown of spheres in liquid nitrogen. Previous analysis by the authors predict the effect of curvature better than other proposed correlations. The heat transfer coefficient increases significantly for the smaller spheres. The Bond number is shown to be a significant correlating parameter illustrating different heat transfer behavior for the large and small spheres.

Important references:

1. Hamill, T. D. and Baumeister, K. J., NASA Tech. Note D-3925 (Aug 1967).
2. Breen, B. D and Westwater, J. W., Chem. Eng. Progr. 58, No. 7, 67-72 (Jul 1962).
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4. Hendricks, R. C. and Baumeister, K. J., NASA Tech. Note D-5124 (Jun 1969).

Key words: Boiling heat transfer; cryobiology; energy balance; film boiling; freezing; heat losses; heat transfer coefficient; heat transfer equipment; heat transfer rates; liquid nitrogen; liquid oxygen; mathematical models; metals; nuclear reactors; pool boiling; size effects; spheres; storage; transportation; tungsten carbide.

A REVIEW ON FILM BOILING

Hsu, Y. Y. (National Aeronautics and Space Administration, Cleveland, Ohio, Lewis Research Center)

Advan. Cryog. Eng. 17, 361-81 (1972)

The author presents a very thorough review of film boiling with considerable emphasis on the analytical (theoretical) approach to the subject. The treatment is general, and the discussion is probably as applicable to oxygen as to any other fluid. [However, one reference is cited which suggests different behavior for nitrogen.]

Subjects covered are: 1) boiling of drops and puddles; 2) pool boiling for various geometries; 3) forced convection film boiling inside channels and tubes. The report offers a good source of film boiling references. Recommendations are made for further work.

Important references:

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2. Brentari, E. G. and Smith, R. V., Advan. Cryog. Eng. 10, 325 (1965).
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4. Bromley, L. A., Chem. Eng. Progr. 46, 221 (1950).
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6. Simon, F. F., Papell, S. S. and Simoneau, R. J., NASA Tech. Note D-4307 (1968).
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9. Park, E. L., Jr., Colver, C. P., and Sliepevich, C. M., Advan. Cryog. Eng. 11, 516 (1966).
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Key words: Aluminum; boiling heat transfer; coatings; droplet formation; film boiling; heat transfer equipment; helium II; jets; Leidenfrost phenomenon; liquid helium; liquid hydrogen; liquid nitrogen; liquid oxygen; metals; orientation effects; pool boiling; saturated liquid; spheres; state-of-the-art reviews; storage; subcooled fluids; superfluid; surface effects; thermal diffusivity; transportation; tubes; vessels; wall temperatures; water.

HEAT TRANSFER FROM BOILING OXYGEN AND NITROGEN

Ivanov, M. E., and Elukhin, N. K.

Kislorod 11, No. 3, 19-28 (1958)

Experiments on heat transfer from oxygen and nitrogen by boiling and convection in single tubes and in a bundle of tubes are documented in this article. Graphs for heat transfer versus specific heat load are given. The investigations have been performed over a wide range of heat loads between 150 kcal/m^2/hr and 200,000 kcal/m^2/hr. Critical loads have been determined at which the boiling process with bubbles yields to film boiling (Q_{crit} about 95,000 kcal/m^2/hr). The experiments have shown hysteresis in the transition region from convection to boiling and inversely.

Key words: Air separation plants; boiling heat transfer; convection heat transfer; equations; film boiling; fluid dynamics; geometry effects; heat transfer coefficient; heat transfer equipment; heat exchanger; hysteresis; liquid nitrogen; liquid oxygen; nucleate boiling; storage; transportation; tube bundles and finned tubing; tubes.

POOL BOILING HEAT TRANSFER TO CRYOGENIC LIQUIDS (3 Parts)
Kosky, P. G. and Lyon, D. N. (California University, Berkeley, California)
A.I.Ch.E. J. 14, 372-87 (1968)

This series of papers is the report of an exhaustive experimental investigation of nucleate pool boiling heat transfer to liquids nitrogen, oxygen, argon, methane, and carbon tetrafluoride. All measurements were performed on the same horizontal, flat, platinum-plated disk. Saturation pressures ranged from 1 atmosphere or less to the immediate vicinity of the critical pressure for each fluid.

In part I, the apparatus is described and measurements of the heat transfer coefficients are reported. These are compared with various suggested nucleate boiling correlations and the correlations of McNelly, of Kutateladze, and of Borishanskiy-Minchenko are found to be roughly equally successful and all distinctly superior to those of Rohsenow, of Gilmour, and of Forster and his collaborators for these liquids. For oxygen, argon, methane, and carbon tetrafluoride, boiling hysteresis of a type not previously reported was observed at intermediate and high saturation pressures on this surface.

In part II, peak nucleate boiling fluxes are reported and these are also compared with correlations. The correlation proposed by Chang and Snyder and various other investigators is superior, for these liquids, to those of Addoms, Noyes, Borishanskiy, and Moissis and Berenson. The P.N.B.F. on a given surface is found to be reproducible to within a few percent, but exposure of that surface to other test liquids or even to the laboratory atmosphere can produce changes of ± 15 percent.

Nucleate boiling curves and peak nucleate boiling fluxes for oxygen-nitrogen mixtures of 3.25, 8.35, and 68.5 mole percent oxygen and for carbon dioxide-free air mixtures are reported in part III.

The nucleate boiling correlations of Kutateladze and of Borishanskiy-Minchenko, which were successful for the pure components, fail for the mixtures at elevated pressures. Of the correlations tested, that of McNelly is most nearly successful for both pure components and for their mixtures at all pressures.

The Chang-Snyder form of the Kutateladze correlation for the P.N.B.F. is successful for mixtures up to $Pr = 0.75$, beyond which it overpredicts the P.N.B.F. No anomalies in P.N.B.F. at 1 atmosphere similar to those reported for binary aqueous systems were observed.

Important reference:

1. Kosky, P. G., Ph.D. Thesis, California University, Berkeley (1966).

Key words: Boiling heat transfer; carbon tetrafluoride; concentration effects; critical region; heat transfer coefficient; horizontal; hysteresis; liquid air; liquid argon; liquid methane; liquid nitrogen; liquid oxygen; mixture; nucleate boiling; plates; platinum; pool boiling; storage; surface effects; transportation.

PEAK NUCLEATE BOILING FLUXES FOR LIQUID OXYGEN ON A FLAT HORIZONTAL PLATINUM SURFACE AT BUOYANCIES CORRESPONDING TO ACCELERATIONS BETWEEN -0.03 and 1 g_E

Lyon, D. N., Jones, M. C., Ritter, G. L., Chiladakis, C. I., and Kosky, P. G.
(California University, Berkeley, California)

A.I.Ch.E. J. 11, No. 5, 773-80 (Sep 1965)

Peak nucleate boiling fluxes for liquid oxygen near 1 atmosphere have been measured on a 0.75-in. diameter flat polished horizontal platinum surface located in a known, variable magnetic-field gradient that produced steady accelerations (which could be maintained indefinitely) on the oxygen acting in opposition to the earth's gravitation, g_E. Measurements were made under conditions ranging from net negative (directed away from the heated surface) accelerations of -0.03 g_E acting on the bulk liquid to the normal acceleration, 1.0 g_E. The results indicate that at zero g conditions for the bulk liquid, the peak nucleate boiling flux is ~ 0.55 of the value at 1.0 g_E. For bulk-liquid accelerations ranging from ~ 0.25 to 1 g_E, the experimental results confirm the 1/4 power dependence of peak flux on acceleration as predicted by various correlations. However, below 0.25 g_E the peak flux becomes insensitive to the acceleration, varying approximately in proportion to the 1/14 power of the net acceleration. At bulk-liquid conditions of zero g (± 0.005 g_E), the peak flux breaks sharply, and falls by a factor of 10 between zero g and - 0.03 g_E.

For a discussion of gravic and agravic effects in cryogenic heat transfer, see last reference below.

Important references:

1. Usiskin, C. M. and Siegel, R., J. Heat Transfer 83, 243 (1961).
2. Merte, H. and Clark, J. A., J. Heat Transfer 83, 233 (1961) and Advan. Cryog. Eng. 7, 546 (1962).
3. Sherley, J. E., Advan. Cryog. Eng. 8, 495 (1963).

See also:

1. Clark, J. A., Advances in Heat Transfer 5, 325-517 (1968).

Key words: Acceleration effects; boiling heat transfer; equation; flat plates; gravity effects; heat transfer rates; liquid oxygen; magnetic field; missiles and rockets; nucleate boiling; peak nucleate boiling flux; platinum; spacecraft; storage; transportation.

HEAT TRANSFER TO BOILING LIQUIDS AT LOW TEMPERATURES AND ELEVATED PRESSURES

Monroe, A. G., Bristow, H. A. S., and Newell, J. E.

J. Appl. Chem. (London) 2, 613-24 (Nov 1952)

The paper reports an extensive study of boiling of oxygen and nitrogen flowing inside tubes at pressures from atmospheric to critical, and of heat transfer above the thermodynamic critical point.

For boiling, the results for the heat transfer coefficient and its relationship to conventional correlation parameters for nitrogen and oxygen are shown to be very close. Most of the boiling data is in the metastable transition region, between the maximum nucleate heat flux and the minimum film heat flux. The boiling data seemed to be in general agreement with nucleate and film boiling studies, although few if any data had been reported in this region.

Above the thermodynamic critical point, the heat transfer coefficient was appreciably improved by both increases in pressure and flow rate. There were indications that the flow was viscous. Fluid temperature and wall-to-fluid temperature differences were shown to be significant variables also.

Important references:

1. Haselden, G. G. and Peters, J. I., Trans. Inst. Chem. Engrs. (London) 27, 201 (1949).

2. Weil, L. and Lacaze, A., C. R. Acad. Sci. (Paris) 230, 186 (1950).

Key words: Boiling heat transfer; copper; film boiling; heat transfer coefficients; inside tubes; liquid nitrogen; liquid oxygen; metastable boiling; nitrogen; nucleate boiling; Nusselt number; oxygen; Reynolds number; supercritical fluids; supercritical heat transfer; tubing; vertical.

BOILING HEAT TRANSFER FOR CRYOGENS

Seader, J. D., Miller, W. S., and Kalvinskas, L. A. (Rocketdyne, Canoga Park, Calif.) National Aeronautics and Space Administration, Huntsville, Ala., Contractor Report No. CR-243 (Jun 1965)

This is a very comprehensive review with 353 references, including graphically presented data for fluid properties required in the proposed expressions to describe the boiling phenomenon. Specific subjects treated are pool, forced and natural convection boiling, geometry and other pertinent conditions such as surface effects, vortices, gravitational effects, electrical fields and agitation for both experimental and theoretical studies.

Particularly useful tables are presented to summarize theoretical approaches to nucleate boiling, nucleate boiling maximum heat flux, and film boiling minimum heat flux.

Experimental and analytical results are compared and those analytical results which fall within the spread of the experimental data indicated. This information serves as a useful guide to designers. Recommendations emphasize the need for more experimental data to determine the apparent disagreements between the rather meager experimental data reported to date for both pool and forced convection boiling. Studies of the surface and geometry effects are also strongly recommended.

This is a very thorough and detailed report and is a valuable reference for any studies involving the boiling of cryogenic fluids.

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3. Bromley, L. A., Chem. Eng. Progr. 46, 221-7 (1950).
4. Clark, J. A. and Merte, H., Paper presented at the XIth International Congress of Refrigeration, Munich, Germany, Aug 27-Sept 4, 1963.
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6. Haseldon, G. G. and Peters, J. I., Trans. Inst. Chem. Eng. (London) 27, 201-8 (1949).
7. Haseldon, G. G. and Prosad, S., Trans. Inst. Chem. Eng. (London) 27, 195-200 (1949).
8. Lyon, D. N., California University, Berkeley, Calif., Low Temperature Laboratory Dept. (1963).
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19. Kutateladze, S. S., Int. J. Heat Mass Transfer 4, 31-45 (1961).

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21. Berenson, P. J., MIT Heat Transfer Laboratory, Cambridge, Mass., Technical Rept. No. 17 (Mar 1960).

22. Moissis, R. and Berenson, P. J., J. Heat Transfer, 85, 221-9 (Aug 1963).

Key words: Agitation; boiling heat transfer; density; electric fields; equations; film boiling; flow rates; forced convection; geometry effects; gravity effects; heat of vaporization; horizontal; inside tubes; liquid hydrogen; liquid nitrogen; liquid oxygen; maximum heat flux; minimum heat flux; natural convection; nucleate boiling; outside tubes; plates; pool boiling; saturated liquids; specific heat at constant pressure; storage; subcooled liquids; surface effects; surface tension; thermal conductivity; transportation; tubing; vapor pressure; vertical; viscosity; vortices; wires.

HEAT TRANSFER FROM CONDENSING OXYGEN AND NITROGEN VAPORS
Haselden, G. G., and Prosad, S.
Trans. Inst. Chem. Eng. 27, 195-200 (1949)

Heat transfer coefficients were measured for oxygen, nitrogen and nitrogen-rich mixtures condensing on a vertical cylindrical surface cooled by boiling liquid nitrogen or oxygen. Pressures ranged from 1.1 to 6 atm. The apparatus was carefully designed as a test of the Nusselt theory of condensation and thus vapor drag on the liquid film was avoided as were turbulence in the liquid film and excessive liquid subcooling. The experimental heat transfer coefficients were in excellent agreement with the Nusselt theory for the pure vapors, but less satisfactory for the mixtures. In view of what the authors set out to do, the results should not be applied indiscriminately; it would be improper to apply the results to condensation inside tubes, for example, where the Nusselt conditions would be violated. For extensions of the Nusselt theory, see references below.

Important later references:

1. Sparrow, E. M. and Gregg, J. L., J. Heat Transfer 81, 13-8 (1959).
2. Koh, J. C. Y. and Sparrow, E. M., Int. J. Heat Mass Transfer 2, 69-82 (1961).

Key words: Boiling heat transfer; condensation heat transfer; film condensation; gaseous nitrogen; gaseous oxygen; heat transfer coefficients; mixture; Nusselt theory; outside tubes; Reynolds number; storage; transportation; tubing; vertical.

HEAT TRANSFER FROM CONDENSING OXYGEN, NITROGEN, AND ARGON
Ivanov, M. E., and Elukhin, N. K.
Kislorod 12, No. 1, 5-12 (1959)

The heat transfer from oxygen, nitrogen and argon condensing in vertical tubes was investigated at various heat loads over the entire range of working conditions for condensers and evaporators of air-separation plants. The results are as follows: 1) at very low heat loads, heat transfer is much influenced by frozen impurities being deposited on the surface; 2) at moderate heat loads the impurities exert no influence on the process and the heat transfer goes on at the expense of thermal conductivity; 3) at high heat loads, convection exerts a considerable influence on heat transfer.

Equations for calculating heat transfer for these three cases are given.

Key words: Air separation plants; argon; condensers; condensing heat transfer; convection; geometry effects; heat transfer equipment; impurity effects; loads; nitrogen; oxygen; particulates; storage; surface effects; thermal conductivity; transportation; tubes; vaporizers; vertical.

COOLING OF CRYOGENIC LIQUIDS BY GAS INJECTION

Larsen, P. S., Clark, J. A., Randolph, W. O., and Vaniman, J. L.
(Michigan University, Ann Arbor, Michigan)

Advan. Cryog. Eng. 8, 507-20 (1963)

Analytical studies of the injection-cooling process have been reported by Randolph and Vaniman (1961) who evaluated the lumped system transient under simultaneous effects of liquid evaporation, ambient heating, and gas enthalpy flux. The analysis compares favorably with experimental data of Halbrooks (1961) for the cooling of liquid oxygen by helium injection and the work of Schmidt (1963) with liquid hydrogen.

This paper presents a theoretical analysis of the process of injection cooling for a space system, including the effects of liquid evaporation, gas solubility, gas enthalpy flux, ambient heating, and liquid displacement due to the presence of gas bubbles in the system. Closed-form solutions are obtained for the cooling transient and the maximum subcooling attainable, and the analysis is compared with existing experimental data.

For the process of injection cooling considered here, the prime concern is that of obtaining and/or maintaining a certain subcooling of a given liquid. Since gas injection is considered to take place for only a relatively short time, the cooling transient is of interest as well as the highest attainable subcooling approached if injection were to be continued for a long period of time.

Average system temperature transients obtained from (1) 15 foot high, 6 inch diameter, and (2) 8 foot high, 17 1/2 inch diameter test columns were compared with theory, assuming zero solubility of helium in liquid oxygen in the first case. While agreement is good for the asymptotic (highest attainable subcooling) temperature in both columns, the predicted cooling rate was too high for the tall column; this may be ascribed to insufficient dispersion of the gas or pronounced bubble coalescence in the tall narrow column.

For the case of gaseous nitrogen injected into liquid oxygen - nitrogen being a non-condensing gas of high solubility in liquid oxygen - the asymptotic temperature appeared to be reasonably predictable but the system transient was poorly described. The cooling rate, being higher than that predicted from equilibrium data, seems to indicate that gas-to-liquid mass transfer rates are insufficient to establish the equilibrium composition in the liquid phase, i. e., equilibrium cannot exist until a certain amount of gaseous nitrogen is completely dissolved in the liquid oxygen.

Experimental data on the cooling of liquid hydrogen by helium injection compared favorably with the present theory in the range of low relative subcooling, where equilibrium data are fairly reliable. Accurate analytical predictions for greater subcooling, obtainable by precooling the injected gas to a temperature near the system temperature, were not possible at the time of this analysis because of the lack of phase-equilibrium data for the hydrogen-helium system.

Important references:

1. Randolph, W. O. and Vaniman, J. L., National Aeronautics and Space Administration, Huntsville, Alabama, George C. Marshall Space Flight Center, Publication No. MTP-S&M-P-61-19 (Oct 1961).

2. Halbrooks, W. J., National Aeronautics and Space Administration, Huntsville, Alabama, George C. Marshall Space Flight Center, Internal Note M-Test No. 13-61 (Aug 1961).

COOLING OF CRYOGENIC LIQUIDS BY GAS INJECTION
Larsen, P. S., Clark, J. A., Randolph, W. O., and Vaniman, J. L.

Important references (continued):

3. Clark, J. A., Merte, H., et al., Michigan Univ., Ann Arbor, Research Inst. Progress Report No. 18, UMRI Project 2646 (Oct 1959).

4. Morgan, S. K. and Brady, H. F., Advan. Cryog. Eng. 7, 206 (1962).

5. Schmidt, A. F., Advan. Cryog. Eng. 8, 521 (1963).

6. National Aeronautics and Space Administration, Huntsville, Alabama, George C. Marshall Space Flight Center, Memorandum M-S&M-PE No. 327 (Oct 1961).

7. Randolph, W. O. and Vaniman, J. L., National Aeronautics and Space Administration, Huntsville, Alabama, George C. Marshall Space Flight Center, Publication No. MTP-M-S&M-P-61-3 (Jan 1961).

Key words: Cooling; fill lines; friction; gas bubbles; gas injection; helium; injection cooling; liquid oxygen; mathematical model; nitrogen; piping; pumps; simulation tests; size effects; solubility; spacecraft tankage; storage; subcooling; theoretical studies; transportation.

SUBCOOLING OF CRYOGENIC LIQUIDS BY INJECTION OF NONCONDENSING GAS
Randolph, W. O., and Vaniman, J. L. (National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Huntsville, Alabama)
National Aeronautics and Space Administration, Huntsville, Alabama, George C. Marshall Space Flight Center, Publication No. MTP-S&M-P-61-19 (Oct 1961)

Subcooling of cryogenic liquids by injection of a noncondensing gas has been investigated as a means of preventing excess heating of liquid oxygen in the suction lines of the Saturn booster during prelaunch. Because of ambient heating, liquid oxygen at the pump inlet approaches the saturation state, precluding successful bootstrapping of the H-1 engine during start.

The cooling of a volatile liquid by evaporation into bubbles of an injected noncondensing gas of low solubility (injection cooling) was found to be effective and applicable to this problem. Because of weight restrictions and simplicity of operation, injection cooling is preferable to conventional methods, especially when local and short-duration subcooling is required.

During the evaporation of liquid oxygen, the heat required is removed from injected helium gas bubbles and from the surrounding liquid oxygen. Oxygen temperature will decrease until the heat transferred to the liquid equals the heat removed in the vaporization process.

The analytical model developed here is simply an overall heat balance of the contained liquid cryogen,

$$q = q_1 + q_2 - q_3 ,$$

where q is the total system heat flux, q_1 the environmental heat flux, q_2 the injected gas heat flux, and q_3 the evaporative cooling rate. With the simplifying assumptions of instantaneous cool-down of the injected gas to the temperature of the liquid cryogen and instantaneous diffusion of the cryogen vapor into the injected gas (the model does not apply for systems where significant diffusion of gas to liquid occurs, such as nitrogen gas in liquid oxygen), agreement is excellent between theory and experiment where helium gas is injected into liquid oxygen and liquid nitrogen. Subsequent work with helium gas in liquid hydrogen also substantiated the general applicability of this analytical approach.

Important references:

1. Randolph, W. O. and Vaniman, J. L., National Aeronautics and Space Administration, Huntsville, Alabama, George C. Marshall Space Flight Center, Publication No. MTP-S&M-P-61-3 (Jan 1961).

2. Halbrooks, W. J., National Aeronautics and Space Administration, Huntsville, Alabama, George C. Marshall Space Flight Center, Internal Note M-Test No. 13-61 (Aug 1961).

Key words: Cooldown; engine restart capability; engine restarts; evaporation; gas injection; heat balance; heat leaks; heat of vaporization; injection cooling; liquid hydrogen; liquid nitrogen; liquid oxygen; mass transfer; mathematical models; missiles and rockets; oxygen pumps; pressurization failures; pumps; rocket engines; saturated liquid; solubility; spacecraft; storage; subcooling; transfer lines; transportation.

HEAT TRANSFER TO BOILING LIQUIDS AT LOW TEMPERATURES AND ELEVATED PRESSURES
Monroe, A. G., Bristow, H. A. S., and Newell, J. E.
J. Appl. Chem. (London) 2, 613-24 (Nov 1952)

The paper reports an extensive study of boiling of oxygen and nitrogen flowing inside tubes at pressures from atmospheric to critical, and of heat transfer above the thermodynamic critical point.

For boiling, the results for the heat transfer coefficient and its relationship to conventional correlation parameters for nitrogen and oxygen are shown to be very close. Most of the boiling data is in the metastable transition region, between the maximum nucleate heat flux and the minimum film heat flux. The boiling data seemed to be in general agreement with nucleate and film boiling studies, although few if any data had been reported in this region.

Above the thermodynamic critical point, the heat transfer coefficient was appreciably improved by both increases in pressure and flow rate. There were indications that the flow was viscous. Fluid temperature and wall-to-fluid temperature differences were shown to be significant variables also.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 24.)

HEAT TRANSFER TO FLUIDS IN THE REGION OF THE CRITICAL TEMPERATURE

Powell, W. B. (Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California)

Jet Propul. 27, No. 7, 276-83 (1957)

Heat transfer coefficients are reported for oxygen in forced convection in the region of the critical temperature for both subcritical and supercritical pressures. Data are presented as a generalized heat transfer coefficient

$$h' = \frac{q}{T_W - T_B}\left(\frac{D^{0.2}}{G^{0.8}}\right)$$

where q is the heat flux, T_W and T_B are wall and bulk temperatures respectively, D is the tube diameter and G the mass flow rate per unit cross sectional area. This term, according to the Dittus-Boelter equation, would reach a maximum at the transposed critical temperature. The authors in fact find a minimum, but the significant fact that has been later brought out by Hendricks, et al. (1970) is that wall temperatures were high in this experiment. A single line plotted for low wall temperatures is in fact increasing below the transposed critical. Other experiments in other fluids show maxima or minima depending on the wall temperatures.

Important later references:

1. Hendricks, R. C., Simoneau, R. J. and Smith, R. V., NASA Tech. Note D-5886 (Nov 1970).

Key words: Convection heat transfer; critical region; forced convection; gaseous oxygen; heat transfer coefficient; high wall temperatures; oxygen; regenerative cooling; rocket engines; stainless steel; supercritical fluids; supercritical heat transfer; tubing; vertical.

HEAT TRANSFER TO WATER, OXYGEN AND CARBON DIOXIDE IN THE APPROXIMATELY CRITICAL RANGE

Shitsman, M. E.

Teploenergetika 6, No. 1, 68-72 (1959) [English Translation RTS 1229, National Lending Library for Science and Technology, Boston Spa, Yorkshire, England]

A study is reported of the general problem of heat transfer to a supercritical fluid flowing in a straight tube beyond the entrance region. Despite an apparent contradiction between previously reported data for water on the one hand (which shows a maximum in the heat transfer coefficient near the critical temperature) and for oxygen on the other (showing a minimum), a good correlation of these data was obtained. The correlation was of the usual form for the dimensionless criteria of convective heat transfer, with the exception that, while Nusselt and Reynolds numbers were evaluated at bulk stream temperature, the Prandtl number selected was the lesser of bulk stream and wall values. In this way the deviation of experimental results from the proposed formula was less than 20 percent for the majority of points.

The authors go on to give an explanation of the apparent water-oxygen contradiction by calculating the heat transfer coefficient from their formula for different values of stream and wall temperatures. They conclude that the experimentally observed behavior for the stream at its critical temperature depends on the temperature dependencies of viscosity and thermal conductivity and on the wall temperatures used.

Important references:

1. Miropolskii, Z. L. and Shitsman, M. E., Zh. Tekh. Fiz. 27, No. 10 (1957).
2. Miropolskii, Z. L. and Shitsman, M. E., Energomashinostroenie, No. 1, (1958).
3. Dickinson, N. L. and Welch, C. P., Trans. ASME 80, No. 3 (1958).
4. Powell, W., Jet Propul. 27, No. 7 (1957).
5. Bringer, R. P. and Smith, J. M., A.I.Ch.E. J. 3, No. 1 (1957).

See also:

1. Hendricks, R. C., Simoneau, R. J. and Smith, R. V., Advan. Cryog. Eng. 15, 197-237, (1970).

Key words: Carbon dioxide; critical region; flow rates; heat transfer rates; liquid; liquid oxygen; Nusselt number; oxygen; Prandtl number; Reynolds number; supercritical heat transfer; thermal conductivity; viscosity; water.

COMPUTED TOTAL RADIATION PROPERTIES OF COMPRESSED OXYGEN BETWEEN 100 AND 1000 K

Jones, M. C. (Cryogenics Division, Institute for Basic Standards, National Bureau of Standards, Boulder, Colorado)

To be published in Int. J. Heat Mass Transfer 15 (1972)

The total emissivity, total band absorptance and Planck mean absorption coefficient of compressed oxygen were computed in the temperature range 100 to 1000 K. Computations were based on published data for the spectral absorption coefficient and extrapolations above and below room temperature were performed in accordance with published theory. It was found possible to represent all of the total band absorptance results with a two-parameter correlation.

Important references:

1. Shapiro, M. M. and Gush, H. P., Can. J. Phys. 44, 949-63 (1966).

2. Bosomworth, D. R. and Gush, H. P., Can. J. Phys. 43, 751-69 (1965).

3. Tien, C. L. and Lowder, J. E., Int. J. Heat Mass Transfer 9, 698-701 (1966).

Key words: Compressed gases; emissivity; frequency effects; gaseous oxygen; infrared radiation; liquid oxygen; optical properties; optical spectra; radiation heat transfer; subcooled liquid; temperature effects; theoretical studies; ultraviolet radiation.

DESIGN OF WATER-TO-CRYOGEN HEAT EXCHANGERS WITH VARIABLE-THICKNESS ICE FILMS

Bowers, W. M. (Rocketdyne, Canoga Park, Calif.)

Advan. Cryog. Eng. 16, 482-93 (1971)

Experimental data are given on a water-to-oxygen heat exchanger designed to vaporize oxygen. An analytical solution is proposed and shown to produce reasonably good results and to be in a form useful to designers. The solution is limited to steady state flow.

Important references:

1. Williamson, K. D. and Bartlitt, J. R., Advan. Cryog. Eng. 11, 561 (1966).

Key words: Computer program; heat exchangers; heat transfer equipment; heat transfer rates; ice formation; liquid oxygen; steady state; vaporizers; water.

THE INFLUENCE OF TWISTED TAPES IN SUBCRITICAL, ONCE-THROUGH VAPOR GENERATORS IN COUNTER FLOW

Cumo, M., Farello, G. E., Ferrari, G., and Palazzi, G.
Comitato Nazionale per l'Energia Nucleare, Casaccia (Italy),
Centro di Studi Nucleari Lab. Rept., 26 pp

This paper presents a study of heat transfer with and without the use of twisted tapes to produce swirl flow. Particular emphasis is placed on the burn-out condition (wet-to-dry wall transition). The wall was heated by a warm fluid in counter flow, rather than by Joule heating, to better simulate the situation in liquid metal cooled reactors. Experimental fluids used were freon 12 and water.

Substantial increases (a factor of two) in the heat transfer coefficient and in the energy to produce burn-out or dry-out result from the introduction of the tapes.

Important references:

1. Bergles, A. E., Fuller, W. D and Hysek, S. J., Int. J. Heat Mass Transfer 14, 1343-54 (1971).

2. Bähr, A., Herkenrath, H. and Mörk-Mörkenstein, P., EUR/C-IS/785/68e, Ispra, Italy.

Key words: Boiling; burnout; convection heat transfer; forced convection; freon 12; heat exchanger; heat transfer coefficient; heat transfer equipment; liquid oxygen; Reynolds number; saturated liquid; sodium; storage; subcooled fluid; superheated; swirl flow; transportation; tubes; water.

SATURN BOOSTER LIQUID-OXYGEN HEAT EXCHANGER DESIGN AND DEVELOPMENT

Platt, G. K., and Wood, C. C. (National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Huntsville, Alabama)

Advan. Cryog. Eng. 7, 296-302 (1962)

A heat exchanger is described which vaporizes liquid oxygen from the main Saturn booster liquid oxygen pumps and provides gas at 40 - 80°F for tank pressurization. The heat is supplied by the pump turbine exhaust. Design methods are detailed which led to the choice of two parallel liquid oxygen paths through concentrically coiled helical tubes of 0.75 in. diameter. Hot turbine exhaust gas flows in a single pass over the tubes in the direction of the helix axis.

Bench tests of the heat exchanger confirmed the design performance when plotted as oxygen gas exit temperature vs. liquid oxygen flow rate. An overall heat transfer coefficient of the order of 70 - 120 Btu/ft^2-hr. -°F could be maintained if the carbon deposited from the turbine exhaust was cleaned after each run.

The authors encountered severe pressure and flow oscillations in the liquid oxygen flow when the exchanger was in the clean condition. They are interpreted as arising from a high heat flux in the boiling section of the heat exchanger and were remedied in this particular case by coating the first seven outer and nine inner coils with a "tar-like" substance. The authors include a discussion of the use of cavitating venturis or orifices on the liquid inlet to eliminate the oscillations.

Key words: Boiling heat transfer; carbon; cavitating venturis; cleaning; coatings; flight vehicle tankage; flow oscillations; flow rates; gas generators; heat exchangers; heat transfer coefficient; heat transfer equipment; instability; insulation; liquid oxygen; missiles and rockets; pressure oscillations; pressurization; pressurization failures; pressurization systems; tar; vaporizers.

THEORETICAL ANALYSES OF CRYOGENIC HEAT PIPES

Chi, S. W., and Cygnarowicz, T. A. (Catholic University of America, Washington, D.C.)

American Society of Mechanical Engineers Space Technology and Heat Transfer Conference, Los Angeles, California (Jun 1970) Paper No. 70-HT/SpT-6

The theoretical analysis of Cotter (1965) is applied, with modifications, to cryogenic heat pipes. First, the maximum heat carrying capacity is related to the properties of the working fluid and it is shown that for a given heat pipe the capacity is proportional to the liquid transport factor. This is the product of liquid density, surface tension, and latent heat, divided by the liquid viscosity. This factor is plotted against temperature for a variety of fluids ranging from hydrogen to sodium and it is seen to cover three decades with the cryogenic fluids having the lowest values. Oxygen is an order of magnitude better than hydrogen and nitrogen falls between.

Next, an expression for the temperature drop along the heat pipe is derived for a given heat current. It is shown that cryogenic heat pipes deviate from the isothermal idealization and that most of the temperature drop is through the liquid. With liquid properties evaluated at a bulk mean temperature, the performance of a nitrogen heat pipe reported by Haskin (1967) is fairly well predicted.

Finally, the maximum heat carrying capacity of the pipe is calculated on the basis of capillary-limited liquid flow with liquid properties evaluated at the bulk mean temperature. Design charts are drawn up for a nitrogen heat pipe with temperature drop plotted vs. temperature of the condenser for various wick thicknesses; an envelope is drawn for the temperature difference at maximum heat carrying capacity. These charts would be conservative for a liquid oxygen heat pipe.

Important references:

1. Cotter, T. P., Los Alamos Scientific Lab., N. Mex., Report No. LA-3246-MS (1965).

2. Haskin, W. L., Wright-Patterson AFB, Ohio. Rept. No. AFFDL-TR-66-228 (1967).

Key words: Ammonia; argon; capillary; carbon tetrafluoride; cesium; condensers; fluorine; heat flux density; heat of vaporization; heat pipe; heat transfer equipment; hydrogen; liquid hydrogen; liquid nitrogen; liquid oxygen; mathematical model; methane; neon; performance data; pressure drop; refrigeration systems; sodium; temperature rise; thermal conductivity; vaporizers; water.

THEORETICAL INVESTIGATIONS OF HYDROGEN, NITROGEN, AND OXYGEN HOMOGENEOUS- AND ANNULAR-WICK HEAT PIPES

Paulius, G., and Lang, S. B., (McGill University, Montreal, P.Q., Canada)
American Society of Mechanical Engineers Winter Annual Meeting, Washington, D.C. (Nov/Dec 1971) Paper No. 71-WA/HT-13

The authors present a fairly detailed analysis of pressure drop in a cryogenic heat pipe. The development essentially follows that of Cotter (1965). Pressure drop in the gas phase is calculated for both laminar and turbulent flow, and for effects of suction and blowing (condenser and evaporator). Liquid phase pressure drop is based on Poiseuille's law with allowance for tortuosity and branching. Interphase pressure drop is calculated on the basis of kinetic theory, and the pressure drop across curved interfaces is based on the well-known Laplace equation.

The analysis is extended from the usual case of a homogeneous wick to that of an annular wick in which the limiting liquid wick pressure drop is greatly reduced by allowing free liquid flow in an annulus behind the wick, which is now simply a cylindrical screen. Liquid pressure drop is now calculated from Poiseuille's law for a thin annulus. Also in this case the pressure drop of the liquid through the screen is calculated.

On the basis of these considerations, numerical studies were made of the expected performance of various heat pipes working with oxygen, nitrogen, and hydrogen. The capillary limited maximum heat flow is plotted against temperature for both homogeneous- and annular-wick heat pipes, and the superiority of the latter is noted. Oxygen is superior in both cases to the other cryogens. Graphs of relative pressure drop contributions illustrate the importance of the interphase pressure drop in annular-wick heat pipes.

The authors present an explanation for the high heat fluxes obtained by Haskin in an ostensibly homogeneous-wick heat pipe. These heat fluxes (~ 100 W) far exceed the values calculated by the theory presented (4.5 W). It is hypothesized that a considerable excess of liquid resulted in a pool being present above the wick. This short-circuited the wick flow and accidentally produced a heat pipe of the annular-wick type.

Important references:

1. Cotter, T. P., Los Alamos Scientific Laboratory, N. Mex. Report No. LA-3246-MS, (1965).
2. Haskin, W. L., Wright-Patterson AFB, Ohio, Rept. No. AFFDL-TR-66-228 (1967).
3. Chi, S. W. and Cygnarowicz, T. A. (Catholic University of America, Washington, D.C.) American Society of Mechanical Engineers Space Technology and Heat Transfer Conference, Los Angeles, California (Jun 1970) Paper No. 70-HT/SpT-6.

Key words: Annuli; capillary; heat flux density; heat of vaporization; heat pipe; heat transfer equipment; heat transfer rates; laminar flow; liquid hydrogen; liquid nitrogen; liquid oxygen; pressure drop; spacecraft; turbulent flow; two-phase flow.

A REVIEW OF PRESSURIZATION, STRATIFICATION AND INTERFACIAL PHENOMENA
Clark, J. A. (Michigan University, Ann Arbor, Mich.)
Advan. Cryog. Eng. 10, (Sects. M-U) 259-83 (1965)

These phenomena (pressurization, stratification and interfacial processes) are closely interrelated, and successfully predicting their behavior is very important to propellant tank design and pumping and transfer systems. This review is quite thorough, with 69 references cited.

The paper is primarily concerned with analytical approaches to the problem. Apparently, reported experimental data are limited and often lacking in sufficient detail to allow conclusive assessment of the various analytical approaches or of their assumptions.

Pressurization (as discussed here) is simply the introduction of gas to the ullage space of a cryogenic fluid storage vessel, where the pressure of the incoming gas is initially greater than that of the stored fluid. The process should be carried out in such manner that the mass of pressurant gas used is minimized and the resulting non-homogeneous density distributions should be predictable. This stratification can cause pumping and venting problems and large pressure fluctuations if the stored cryogen is suddenly mixed.

Analytical approaches may be divided into the following categories —

For processes and properties:

1. Lumped systems - dealing with mean property values of the gas and wall as a function of time.

2. Distributed systems - in which temperature, density and velocity are determined as a function of space and time.

For the solution to analytical expressions:

1. Closed form - where proper assumptions are made to formulate expressions allowing this type of solution.

2. Numerical - where step-wise integration is performed essentially without the simplifying solutions of the closed form (above).

There are also semi-empirical approaches resulting in useful correlations.

The author states that experience to date allows the following conclusions: Minimum gas residual is achieved by maximizing inlet gas temperature, minimizing its pressure, and selecting a pressurant with low molecular weight and high heat capacity. Interface heat transfer is negligible with respect to wall heat transfer.

Stratification can result from pressurization and from the distribution of heat transferred to the cryogen during storage. When energy is added at a vertical wall, there is an upward flow of low density fluid near the wall; if, as for the usual case, there are no forces to provide mixing or downward flow of the low density layer into the higher density region, this low density fluid forms a warmer, low density layer at the top of the stored cryogen. The undesirable results of stratification are mentioned previously. Analytical approaches can follow the same categories as those for pressurization but most are for numerical solutions of distributed systems. A number of predictive methods have been proposed differing rather widely in approach. Satisfactory agreement with experiments has been achieved in some cases but insufficient data are available to judge the relative merit of the various approaches.

Interfacial phenomena, or the transport of energy and mass (vaporization or condensation) at the interface, plays an important part in the pressurization and

A REVIEW OF PRESSURIZATION, STRATIFICATION AND INTERFACIAL PHENOMENA
Clark, J. A.

(Continued)

stratification processes. Studies to date have achieved some success in predicting the interface process behavior but are not completely conclusive. They do indicate that a) the interface temperature is essentially the saturation temperature for the system pressure, b) during self-pressurization (from heat transfer at the walls), interfacial evaporation occurs and the system pressure is governed by the vapor pressure characteristics of the phases at the interfacial temperature.

Although some guidance for designers has been provided by the works summarized here, a reliable solution required for optimal design has not been achieved for any of the phenomena discussed. An impressive list of unresolved problems is included.

Important references:

1. Nein, M. E. and Thompson, J. F., National Aeronautics and Space Administration, Huntsville, Ala., George C. Marshall Space Flight Center Propulsion Division (Jul 1964).
2. Arpaci, V. S., Clark, J. A. and Winer, W. O., Advan. Cryog. Eng. 6, 310 (1961).
3. Arpaci, V. S. and Clark, J. A., Advan. Cryog. Eng. 7, 419 (1962).
4. Ordin, P. M., Weiss, S. and Christenson, H., Advan. Cryog. Eng. 5, 481 (1960).
5. Nein, M. E. and Head, R. R., Advan. Cryog. Eng. 7, 244 (1962).
6. Epstein, M., Advan. Cryog. Eng. 10 (Sects. M-U), 303-7 (1965).
7. Liebenberg, D. H. and Edeskuty, F. J., Advan. Cryog. Eng. 10 (Sects. M-U), 284-9 (1965).
8. Segel, M., Advan. Cryog. Eng. 10 (Sects. M-U), 308-13 (1965).
9. Vliet, G. C., Brogan, J. J., Sheppard, T. S., Morie, F. H. and Hines, F. L., AIAA Preprint No. 64-37, Aerospace Sciences Meeting, New York, Jan 20-22, 1964.
10. Clark, J. A. and Barakat, H. Z., Michigan University, Ann Arbor, Mich., Heat Transfer Laboratory Technical Rept. No. 1, Contract NAS 8-825 (Jan 1964).
11. Satterlee, H. M. and Reynolds, W. C., Stanford University, Stanford, Calif., Dept. of Mechanical Engineering Technical Rept. No. LG-2 (May 1964).
12. Knuth, E. L., Phys. Fluids 2, No. 1, 84 (Jan-Feb 1959).
13. Yang, W. J., AIChE Preprint No. 48, Sixth National Heat Transfer Conference, Boston, Mass., Aug 11-14, 1963.

Key words: Boundary layer model; condensation; convection heat transfer; evaporation; gaseous oxygen; Grashof number; helium; interface; interfacial phenomena; liquid hydrogen; liquid nitrogen; liquid oxygen; liquid-vapor interface; mass transfer; missiles and rockets; Prandtl number; pressurization; pressurization gas requirements; pressurized discharge; propellant tanks; Rayleigh number; spacecraft; spacecraft tankage; storage; stratification; transportation; ullage space.

FINITE DIFFERENCE SOLUTION OF STRATIFICATION AND PRESSURE RISE IN CONTAINERS

Barakat, H. Z., Merte, H., and Clark, J. A. (University of Michigan, Ann Arbor, Michigan, Department of Mechanical Engineering)

Proceedings of the Conference on Long Term Cryo-Propellant Storage in Space. George C. Marshall Space Flight Center, Huntsville, Alabama (Oct 12-13, 1966) pp. 145-162

The processes of heat and mass transfer interactions between the gas and liquid phases of a single component in cylindrical containers with axial symmetry are considered. In the general formulation attention is given to the cases of external pressurization with and without liquid discharge as well as to the non-vented condition. The governing equations are cast into finite-difference form and numerical computations are carried out for the case of a non-vented container having an imposed heat flux.

Calculations were performed for a reduced gravity field of 10^{-5} g_E for liquid oxygen. Parameters varied were the heat flux through the vessel wall and the initial ullage volume, and pressure-time histories were generated. Also presented are isotherms throughout the system and the total mass of liquid evaporated, both as functions of time.

Important references:

1. Yang, W. J., Larsen, P. S. and Clark, J. A., J. Eng. Ind. 87, 413-8 (1965).
2. Thomas, P. D. and Morse, F. H., Advan. Cryog. Eng. 8, 550-62 (1964).
3. Epstein, M., Georgius, H. K. and Anderson, R. E., Advan. Cryog. Eng. 10, 290-302 (1966).
4. Barakat, H. Z. and Clark, J. A., Proceedings, Third International Heat Transfer Conference, Vol. II (Chicago, Ill., Aug. 7-12, 1966).

See also:

1. Merte, H., Clark, J. A. and Barakat, H. Z., Michigan University, Heat Transfer Laboratory, (Aug 1967).

Key words: Boiling heat transfer; energy balance; equation; evaporation; evaporation rates; finite difference techniques; gravity effects; heat leaks; heat transfer rates; interfacial phenomena; isotherm; laminar flow; leakage and spills; liquid-vapor interface; liquid oxygen; liquid oxygen tank; long term storage; manned spacecraft; mass transfer; nucleate boiling; pressure rise; pressurization; space stations; space storage; space vehicles; spacecraft; spacecraft tankage; storage; stratification; theoretical studies; transportation; turbulent flow; ullage space.

ANALYTICAL METHOD FOR ESTIMATING GAS REQUIREMENTS IN THE PRESSURIZATION AND TRANSFER OF CRYOGENIC FLUIDS

Bowersock, D. C., and Reid, R. C. (Arthur D. Little, Inc., Santa Monica, California)

Advan. Cryog. Eng. 6, 261-71 (1961)

This paper presents a lumped-system analysis of the pressurization and transfer of cryogens from storage tanks. The essence of the particular model chosen is that pressurizing gas may be divided into two parts: A mass of gas which fills the ullage space at inlet temperature and tank pressure, and a mass which is condensed to liquid at tank pressure. It is further assumed that pressurization takes place instantaneously. Other more or less arbitrary assumptions are introduced during the course of the analysis.

Thus the model is a somewhat idealized representation of the rather complicated interactions occurring during pressurization and transfer of cryogens. In spite of this the authors claim that in all but a few of 48 tests conducted, with system sizes varying from 3 to 28,000 gal, using hydrogen, oxygen, or nitrogen, the difference between calculated and experimental gas consumption was less than 10 percent. A table containing information for some of these tests is included with calculated and experimental pressurizing gas consumptions given.

Key words: Liquid hydrogen; liquid nitrogen; liquid oxygen; lumped-system analyses; mathematical models; operational systems and subsystems; pressurant condensation; pressurization analysis; pressurization gas requirements; pressurization systems; pressurized transfer; storage; transportation; ullage space.

PRESSURE PHENOMENA DURING TRANSFER OF SATURATED CRYOGENIC FLUIDS
Canty, J. M. (Linde Company, Tonawanda, New York)
Advan. Cryog. Eng. 6, 272-80 (1961)

This paper deals with pressurization and transfer of cryogenic liquids as saturated liquids at the storage pressure. The pressure build up is achieved by heat leak to the dewar; no pressurizing gas is supplied. Results of computations are presented for the conservative case in which heat leak is zero and, thus, the fall in pressure is the steepest. Results are in the form of graphs of dewar pressure vs. percent withdrawn, starting from a completely filled dewar. The authors also calculate the rate of change of heat input with mass withdrawn necessary to maintain a constant pressure, which may be used to estimate, for a given withdrawal rate, whether pressure will fall or continue rising if the heat leakage is known. Tests on liquid oxygen at approximately zero heat leak per unit mass withdrawn and on liquid nitrogen for constant pressure withdrawal are in reasonable agreement with calculations.

It should be stressed that equilibrium between vapor and liquid in the storage vessel is assumed throughout. The presence of stratification, i.e., non-equilibrium, will result in a much steeper fall in pressure than predicted by this method.

Important references:

1. Canty, J. M. and Gabarro, R., Advan. Cryog. Eng. 4, 154-9 (1960).

2. Schmidt, A. F., Purcell, J. R., Wilson, W. A. and Smith, R. V., Advan. Cryog. Eng. 5, 487-97 (1960).

Key words: Expulsion rates; flow rates; heat leaks; liquid argon; liquid helium; liquid hydrogen; liquid nitrogen; liquid oxygen; pressure buildup; pressure decay; pressurized transfer; saturated liquid; storage; stratification; thermal pressurization; transfer systems; transportation.

PREDICTION OF LIQUID HYDROGEN AND OXYGEN PRESSURANT REQUIREMENTS
Epstein, M. (Rocketdyne, Canoga Park, California)
Advan. Cryog. Eng. 10, 303-7 (1963)

The author presents an equation for predicting gas pressurant requirements during the expulsion of either liquid oxygen or liquid hydrogen from a storage tank when pressurized with either helium or oxygen for liquid oxygen, or helium or hydrogen for liquid hydrogen. Neither the form of the equation nor the significance of its terms is discussed, but the equation is nonetheless useful if simply regarded as a semi-empirical relationship, which represents to within 6 percent the results of over 100 computer calculations. This computer program is described in the first reference below. There are eight empirical constants in the equation whose values were determined by least squares fit to the computer results. Finally the author compares the predictions of his equation to experimental data for liquids oxygen, hydrogen and nitrogen from a variety of sources. The equation predicts the experimental results to within 12 percent.

Important later references:

1. Epstein, M., Georgius, H. K. and Anderson, R. E., Advan. Cryog. Eng. 10, 290-302 (1965).

2. Nein, M. E. and Thompson, J., NASA Tech. Note D3177 (Feb 1966).

Key words: Collapse factor; computer programs; equations; expulsion; flight vehicle tankage; flow rates; gaseous helium; gaseous hydrogen; gaseous oxygen; heat transfer; liquid hydrogen; liquid oxygen; mass transfer; pressurants; pressurization; pressurization analysis; pressurization gas requirements; pressurization system analyses; pressurization systems; pressurized transfer; propellant tanks; size effects; storage.

A GENERALIZED PROPELLANT TANK-PRESSURIZATION ANALYSIS

Epstein, M., Georgius, H. K., and Anderson, R. E. (Rocketdyne, Canoga Park, California)

Advan. Cryog. Eng. 10, 290-302 (1965)

In this paper the authors present a rather general analysis for the pressurization and expulsion of cryogenic propellants from tanks. In a restricted sense this is a distributed system analysis in that axial property and temperature variation is taken into account both in the vapor and the liquid. In another sense this approach should probably be called system modeling because from the sheer complexity of the problem many fundamental processes are represented by arbitrary mathematical forms and arbitrarily chosen constants. The resulting seventeen equations are finally solved numerically after being put in finite difference form.

Some of the features of the analysis are as follows:

1. Any tank form (including annular) which is a surface of revolution may be handled.
2. Diffusion in a binary gas mixture in the gas phase may be handled; hence, the case of pressurizing a liquid with a gas of different species may be handled (liquid oxygen with helium gas).
3. Heat transfer is assumed to occur in both gas and liquid phases by conduction between adjacent axial elements; in the gas phase by convection with adjacent wall elements and with the liquid surface; by convection in the liquid phase with adjacent wall elements; by conduction in the radial direction through the insulation and wall and by convection and radiation from the external surface to the surroundings.
4. Condensation or evaporation is computed at the gas-liquid interface.
5. The characteristics of the pressurant supply system may be combined with the prevailing conditions within the tank to determine the gas flow rate.

The computer program includes the seventeen equations presented plus the equation of state of the gas and equations of the thermal properties. The equations presented are energy, diffusion, and continuity for the gas phase; energy and continuity for the liquid phase; an expression for an effective conductivity as a function of height for both phases; a gas-to-wall heat transfer coefficient as a function of height; an effective gas phase diffusion coefficient as a function of height; a heat balance at the interface which yields the rate of condensation or evaporation; a gas phase boundary layer equation for diffusion of condensing vapor at the interface; equations for both phases expressing the velocity of the gas-liquid interface; effective heat and mass transfer coefficients for the boundary layer; and an energy equation for the temperature of the wall. A final equation simply expresses the assumption that the temperature of the interface is the saturation temperature corresponding to the partial pressure of the liquid component in the gas phase at the interface, the gas being considered as an ideal mixture when a second component is present.

Comparisons between computed and NASA experimental results for liquids oxygen and hydrogen show that the analysis is fairly flexible and capable of modeling quite complicated temperature, pressure, and flow histories and of giving a good representation of axial temperature gradients in the gas phase.

Key words: Computer programs; condensation; conduction heat transfer; convection heat transfer; cryogenic containers; equations; evaporation; gaseous helium; heat transfer coefficient; liquid hydrogen; liquid oxygen; liquid-vapor interface; mass transfer; mathematical models; pressurants; pressure rise; pressurization; pressurization analysis; propellant tanks; spacecraft tankage; storage; storage vessels; transportation.

A STUDY OF LIQUID OXYGEN BOIL-OFF

Harrje, D. T. (Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California)

Jet Propulsion Laboratory, Pasadena, Calif., Memorandum No. 20-138 (Dec 1956)

The boil-off characteristics of liquid oxygen were studied in a series of tests which provided both a constant heat flux at various flux levels and a heat flux which varied with time in a manner similar to that obtained from aerodynamic heating in missile flight.

The cylindrical tank, made of aluminum, was one foot in diameter and 4 feet high. Aerodynamic heating of the tank was simulated by electrically heating 0.004 inch thick stainless steel sheets which were tightly wrapped around the tank and over which were electrical insulation sheets. The thermal insulation surrounding the heating sheet consisted of a 1/8 inch thick woven asbestos mat. It was possible to heat the upper and lower tank sections independently, but only the lower liquid-filled part was heated in these tests.

Tests were conducted with both steady and variable heat input after a 5 second pressurization step to bring the pressure up to 25 psig. The calculated start of boil-off was based on the time required to supply the heat necessary to raise the liquid to saturation. The test data were in general agreement but a more gradual transition was observed and maximum boil-off was not reached until some time later. In these tests a small quantity of boil-off resulting from uneven heating of the liquid preceded the predicted start. Measurements at various locations in the liquid indicated a temperature-time lag which was dependent upon the distance from the wall. The time lag was of the order of 1/2 second/inch of distance from the wall or upper surface. Such a time lag in a large scale tank could be a very significant consideration.

Key words: Aerodynamic heating; boiling heat transfer; boil-off rates; convection heat transfer; heat flux density; heat leaks; heat transfer rates; liquid level sensors; liquid oxygen; liquid oxygen tank; losses; missiles and rockets; pressurization; propellant tanks; saturated liquid; simulation tests; spacecraft; spacecraft tankage; storage; tanks; transportation; uninsulated tank; vaporization; vessels; wall temperatures.

PRESSURIZED TRANSFER OF CRYOGENIC FLUIDS FROM TANKS IN LIQUID NITROGEN BATHS

Humphrey, J. C. (National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio)

Advan. Cryog. Eng. 6, 281-92 (1961)

Experiments were conducted on the pressurization of, and pressurized transfer of liquids oxygen and nitrogen from, small laboratory scale tanks submerged in a bath of liquid nitrogen. Measurements were made of oxygen gas condensation rates into the empty tank and of pressurizing gas consumption rates for the transfer of liquid out of the tank.

The experimental results were interpreted by a straightforward lumped parameter analysis in which an overall heat transfer coefficient was used and was evaluated from one of the condensation runs. Gas consumption was slightly overestimated by this method (2-12 percent). Tests using different pressurizing gases with liquid oxygen showed helium to be a superior pressurant on the basis of gas consumption. A large amount of contamination (6 percent by weight) of oxygen with nitrogen is to be expected when this gas is used as pressurant under these conditions, but it should be borne in mind that this is due to nitrogen condensation; if the tank were not submerged and the liquid oxygen not subcooled, then condensation would only take place for transfer pressures above 50 psia.

These tests also demonstrated the need to avoid direct impingement of pressurizing gas on the liquid surface. The use of a gas flow diffuser is recommended.

Key words: Condensation rates; flight vehicle tankage; heat transfer coefficient; helium; instrumentation; liquid oxygen; lumped-parameter analyses; nitrogen; pressurant condensation; pressure transducers; pressurization failures; pressurization gas requirements; pressurization systems; pressurization systems analysis; pressurized transfer; propellant loading systems; storage; turbine mass flowmeters.

EXPERIENCES WITH PRESSURIZED DISCHARGE OF LIQUID OXYGEN FROM LARGE FLIGHT VEHICLE PROPELLANT TANKS

Nein, M. E., and Head, R. R. (National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Huntsville, Alabama)

Advan. Cryog. Eng. 7, 244-50 (1962)

This paper presents some of the experiences of the Marshall Space Flight Center with pressurized discharge of liquid oxygen obtained during static firings of the Saturn vehicle and with pressurization tests of a liquid-oxygen filled tank of comparable size. One small scale tank was also tested with liquid nitrogen.

By measuring temperature profiles throughout the ullage space and the flow rate of pressurizing gas, the authors were able to infer the mass transfer (evaporation or condensation) in the tank. In the large tanks, evaporation was dominant with about 1.5 times as much gas remaining in the ullage space at the end of transfer as had been supplied as pressurant. In the small tank, using helium as pressurizing gas, evaporation took place at all times; the maximum ratio of rate of gas evaporated to pressurant supplied was 0.2 (cf. 1.50 and 0.69 for Saturn and the other large tank). Using nitrogen as pressurant in the small tank gave condensation at all times with a condensed mass 0.4 times total pressurant gas.

An analysis of the energy balances in the tanks indicated that in the large tanks only a minor fraction of the accumulated inlet enthalpy was lost to the walls of the vessel (about 25 percent) whereas in the small tank this accounted for the major part of the inlet enthalpy (69 percent for helium pressurization and 90 percent for nitrogen pressurization).

Key words: Condensation; enthalpy; evaporation; flight vehicle tankage; gaseous helium; gaseous nitrogen; gaseous oxygen; liquid oxygen; mass transfer; NPSH pressure; pressurization; pressurization gas requirements; pressurized transfer; propellant tanks; size effects; spacecraft tankage; storage; storage tanks; temperature profiles; temperature stratification; ullage pressurants; ullage space.

EXPERIMENTAL AND ANALYTICAL STUDIES OF CRYOGENIC PROPELLANT TANK PRESSURANT REQUIREMENTS

Nein, M. E., and Thompson, J. F., (National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Huntsville, Alabama)

National Aeronautics and Space Administration Tech. Note D-3177 (Feb 1966)

Experimental tests are reported for five tank configurations in which, primarily, liquid oxygen was pressurized and displaced by either gaseous oxygen or helium. The test tanks ranged from the multiple interconnected cylindrical tanks of the Saturn I S-I stage (8980 ft^3) to a small cylindrical tank (2.36 ft^3) and an oblate spheriod for the S-IV oxygen tank (1511 ft^3). In these tests, ullage temperature profiles (axial and radial), gas pressurant flow rates, gas-to-wall heat transfer coefficients, interfacial mass transfer, ullage concentration profiles and tank wall temperatures were measured as a function of time. The effect of sloshing was also investigated. Extensive graphs are given of these test results.

The test results were used to determine some of the arbitrary constants in the computer program reported by Epstein, et al. (1965), and the computer program was modified by changing some of the heat transfer and mass transfer relationships. In effect, the program was modified to give as good account as possible of the many test results available. A fairly impressive representation of the test results was obtained, showing this to be a fruitful approach to the modeling of such a complex process.

Some results of axial temperature profiles were also compared with the closed form solutions of Arpaci, et al. (1961).

Important references:

1. Epstein, M., Georgius, H. K. and Anderson, R. E., Advan. Cryog. Eng. 10, 290-302 (1965).

2. Arpaci, V. S., Clark, J. A. and Winer, W. O., Advan. Cryog. Eng. 6, 310-22 (1961).

Key words: Convection heat transfer; cylindrical vessels; flow rates; free convection; gaseous helium; gaseous nitrogen; gaseous oxygen; geometry effects; heat transfer coefficients; liquid hydrogen; liquid oxygen; liquid oxygen tank; manned spacecraft; mass transfer; mathematical model; missiles and rockets; pressurant gas requirements; pressures; pressurization; pressurization failures; pressurization system analyses; propellant tanks; size effects; sloshing; spacecraft tankage; spherical vessels; storage; tank pressurization systems; transportation; ullage space.

PREDICTION OF THE EFFECTS OF THERMAL STRATIFICATION ON PRESSURE AND TEMPERATURE RESPONSE OF THE APOLLO SUPERCRITICAL OXYGEN TANK

Chen, I. M., and Anderson, R. E. (North American Rockwell Corporation, Space Division, Downey, California)

National Aeronautics and Space Administration, Houston, Texas, Manned Spacecraft Center Cryogenics Symposium Papers, Publ. No. MSC - 04312, (May 20-21, 1971) p. 274

A semi-empirical design-oriented model prediction of the effects of thermal stratification on tank pressure and heater temperature response for the Apollo supercritical oxygen tank is given. The heat transfer formulation describes laminar free convection at low-g and takes into account the radiation and conduction processes occurring in the tank. The non-equilibrium thermodynamic behavior of the system due to localized heating of the stored fluid is approximated by the characteristics of a discrete number of fluid regions and thermal nodes. Solutions to the time dependent variable fluid property problem are obtained through the use of a reference temperature procedure. A criterion which establishes the reference temperature as a function of the fluid density ratio, ρ/ρ_{cr}, is derived. The analytical results compare favorably with the flight data.

Important references:

1. Weber, L. A., J. Res. Nat. Bur. Stand. 74A, No. 1, 93-129 (1970).

2. Hall, W. J., McCarty, R. D. and Roder, H. M., Nat. Bur. Stand. (U.S.) Report No. 9288 (Aug 1967).

Key words: Boundary layers; conduction heat transfer; convection heat transfer; critical heat transfer; critical point; critical region; destratification; electrical heaters; gravity effects; heaters; liquid oxygen; liquid oxygen tank; manned spacecraft; mathematical models; pressure collapse; pressure decay; pressure rise; pressurization; radiation heat transfer; response time; spacecraft tankage; storage; stratification; supercritical storage; transportation; vessels; zero gravity.

E

HEAT TRANSFER AND THERMAL STRATIFICATION IN THE APOLLO 14 CRYOGENIC OXYGEN TANKS

Fineblum, S. S., Haron, A. S., and Saxton, J. A. (Bellcom, Washington, D.C.)

National Aeronautics and Space Administration, Houston, Texas, Manned Spacecraft Center Cryogenics Symposium Papers, Publ. No. MSC - 04312, (May 20-21, 1971) p. 182

Two simplified models were used to gain insight into the thermal behavior of the Apollo supercritical oxygen tanks. In the first, pressure response is analyzed in terms of the behavior of two fluid phases. The basic attributes of the observed pressure behavior are exhibited by a model in which less than 1 percent of the fluid is in the less dense phase surrounding the heater. In the second model, the temperature history is predicted by a multinodal conductive-radiative heat transfer computation and provides the worst case for heater temperature. Agreement with flight data is good for the attitude hold condition, and, as expected, the heater temperature is overpredicted during spacecraft rotation.

Key words: Acceleration effects; breathing oxygen systems; computer programs; conduction heat transfer; convection heat transfer; destratification; electrical heaters; fans; gravity effects; heaters; life support systems; liquid oxygen; liquid oxygen tank; manned spacecraft; mathematical models; mixing; pressure decay; pressurization; spacecraft tankage; storage; stratification; supercritical storage; transportation; vessels.

A NUMERICAL SOLUTION OF THE NAVIER-STOKES EQUATIONS FOR SUPERCRITICAL FLUID THERMODYNAMIC ANALYSIS

Heinmiller, P. J. (TRW Systems Group, Houston, Texas)

National Aeronautics and Space Administration, Houston, Texas, Manned Spacecraft Center Cryogenics Symposium Papers, Publ. No. MSC - 04312, (May 20-21, 1971) p. 131

An explicit numerical solution of the compressible Navier-Stokes equation is applied to the thermodynamic analysis of supercritical oxygen in the Apollo cryogenic storage system. The wave character is retained in the conservation equations, which are written in the basic fluid variables for a two-dimensional Cartesian coordinate system.

Control-volume cells are employed to simplify imposition of boundary conditions and to ensure strict observance of local and global conservation principles. Non-linear real-gas thermodynamic properties responsible for the pressure collapse phenomenon in supercritical fluids are represented by tabular and empirical functions relating pressure and temperature to density and internal energy. Wall boundary conditions are adjusted at one cell face to emit a prescribed mass flow rate. Electrical heater input is treated as localized internal heat generation, a fraction of which may be radiated to the walls where it is added to the prescribed boundary heat flux. The effect of "tank stretch" on dP/dt is included as out-of-plane fluid expansion. Scaling principles are invoked to achieve acceptable computer execution times for very low Mach number convection problems.

Detailed simulations of thermal stratification and fluid mixing occurring under low acceleration in the Apollo 12 supercritical oxygen tank are presented which model the pressure decay associated with destratification induced by an ordinary vehicle maneuver and heater cycle operation.

Important references:

1. Kamat, D. V. and Abraham, W. H., J. Spacecr. Rockets, 5, 184-8 (1968).

Key words: Acceleration effects; analytical models; breathing oxygen systems; convection heat transfer; destratification; elasticity; electrical heaters; equation; gravity effects; heaters; heat leaks; life support systems; liquid oxygen; liquid oxygen tank; manned spacecraft; mathematical models; pressure collapse; pressurization; scaling laws; spacecraft tankage; storage; stratification; supercritical storage; theoretical studies; transportation; vessels; zero gravity.

TEST EVALUATION OF TEMPERATURE STRATIFICATION EFFECT IN GEMINI SUPERCRITICAL OXYGEN SUBSYSTEMS IN A 1-G ENVIRONMENT

Mc Laughlan, P. B. (National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas)

National Aeronautics and Space Administration, Houston, Texas, Manned Spacecraft Center Internal Note No. MSC-IN-65-EP-13 (Jul 1965)

The purpose of the tests reported was to obtain ground test data for correlation and substantiation of flight data obtained on the Gemini GT-2 flight, during which severe pressure decay had been experienced 354 seconds after lift-off in the reactant supply system supercritical oxygen tank. The pressure decay accompanied a 90° roll following second stage separation.

Tests were conducted on a similar oxygen tank (0.72 ft^3 capacity) and a larger tank (1.65 ft^3 capacity) designed for the environmental control system. Both tanks were spherical, double-wall dewars with the inner vessel wrapped with multilayer insulation. Both tanks contained heaters mounted on spherical expanded metal surfaces, and cylindrical capacitance quantity gauging elements. A total of twenty tests were carried out consisting of filling, pressurizing and subsequently rotating the tanks while monitoring pressure decay and quantity gauging system performance. With initial storage pressures of about 800 psig, severe pressure decays of up to some 700 psi were recorded when immediate rotation followed an ambient temperature gas pressurization. Other pressurization means produced less decay and it was generalized that less specific heat input rates produced less decay. Ambient temperature gas pressurization was not considered an acceptable pre-launch pressurization mode but it was concluded that with proper pressurization procedures, pre-launch thermal stratification can be minimized to the extent that a serious problem is not posed.

It should be stressed that this report is not concerned with zero gravity performance which would appear to be more prone to stratification and pressure decay.

Key words: Breathing oxygen systems; capacitance probes; environmental control systems; fluid dynamics; fluid mixing; gravity effects; heaters; instrumentation; liquid oxygen; manned spacecraft; oxygen; pressure decay; pressurization failures; pressurization procedures; quantity gaging instrumentation; space vehicles; storage; storage tanks; stratification; supercritical fluids; readout fluctuations; rotating systems; temperature stratification.

CORRELATION OF APOLLO OXYGEN TANK THERMODYNAMIC PERFORMANCE PREDICTIONS

Patterson, H. W. (The Boeing Company, Space Division, Houston, Texas)

National Aeronautics and Space Administration, Houston, Texas, Manned Spacecraft Center Cryogenics Symposium Papers, Publ. No. MSC - 04312, (May 20-21, 1971) p. 103

This paper presents the results of detailed tank thermodynamic simulations conducted with the numerical mathematical model of C. K. Forester (1971). This model uses a two-dimensional rectangular grid of cells to approximate the flow and temperature fields inside the tank. Simulations were carried out for a range of grid sizes to permit extrapolations of variables to their asymptotic limits. The effects of tank elasticity and heater temperature sensor lag were included and tank pressure and heater temperature were computed as a function of time. The computations were compared with actual Apollo 14 flight data with reasonable success. Heater temperatures were also calculated from an empirical heat transfer relationship. This was found to yield satisfactory agreement with flight data when fluid properties were averaged rather than evaluated at the mean film temperature.

Important references:

1. Forester, C. K., National Aeronautics and Space Administration, Houston, Texas, Manned Spacecraft Center Cryogenics Symposium Papers, Publ. No. MSC - 04312, May 20-21, 1971, p. 45.

Key words: Acceleration effects; breathing oxygen systems; elasticity; equation; fuel cells; gravity effects; heaters; life support system; liquid oxygen; liquid oxygen tank; manned spacecraft; mathematical models; pressure collapse; pressure drop; pressure rise; pressurization; spacecraft tankage; storage; stratification; supercritical storage; thermodynamic analyses; transportation; vessels; zero gravity.

STRATIFICATION CALCULATIONS IN A HEATED CRYOGENIC OXYGEN STORAGE TANK AT ZERO GRAVITY

Suttles, J. T., and Smith, G. L. (National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia)

National Aeronautics and Space Administration, Houston, Texas, Manned Spacecraft Center Cryogenics Symposium Papers, Publ. No. MSC - 04312, (May 20-21, 1971), p. 233

A cylindrical one-dimensional model of the Apollo cryogenic oxygen storage tank was developed to study the effect of stratification in the tank. Zero gravity was assumed, and only the thermally induced motions were considered. The governing equations were derived from conservation laws and solved on a digital computer. Realistic thermodynamic and transport properties were used. Calculations were made for a wide range of conditions. The results show the fluid behavior to be dependent on the quantity in the tank or, equivalently, the bulk fluid temperature. For high quantities (low temperatures), the tank pressure rises rapidly with heat addition, the heater temperature remains low, and significant pressure drop potentials accrue (over 100 psia in 2 hours). For low quantities, the tank pressure rises more slowly with heat addition and the heater temperature becomes high (as much as 500 K). A high degree of stratification resulted for all conditions; however, the stratified region extended appreciably into the tank only for the lowest tank quantity. The calculations also indicate a significant flux of mass from the heater tube for high tank quantities. The results have been compared with Apollo 14 flight data. For attitude hold conditions (i.e., no spacecraft motions), the calculations are in good agreement with the data. For conditions where the spacecraft is spinning, the calculations overpredict the heater temperature and the time for a heater cycle.

Important references:

1. Weber, L. A., Nat. Bur. Stand. (U.S.) Report No. 9710, (Jun 1968).

2. Solami, B. J. and Abraham, W. H., Bendix Technical Journal 3, 34-40 (1970).

Key words: Acceleration effects; breathing oxygen systems; convection; destratification; electrical heaters; fans; fluid quantity; gravity effects; heaters; life support systems; liquid oxygen; liquid oxygen tank; manned spacecraft; mass flow; mass transfer; mathematical models; mixing; pressure collapse; pressure rise; spacecraft tankage; storage; stratification; supercritical storage; transportation; vessels; zero gravity.

HEAT TRANSFER DOMAINS FOR FLUIDS IN A VARIABLE GRAVITY FIELD WITH SOME APPLICATIONS TO STORAGE OF CRYOGENS IN SPACE

Adelberg, M., and Schwartz, S. H. (Douglas Aircraft Co.)

Douglas Aircraft Co. Paper No. 3516 (Aug 1965); also Advan. Cryog. Eng. 11, 568-83 (1966)

Heat transfer domains are identified (and boundaries plotted) for hydrogen and oxygen at 1 atmosphere and at saturation pressures as a function of heat flux and the ratio of the local to standard gravitational acceleration. Applicable heat transfer relations are suggested for the domains, along with some needs for new criteria.

The primary application for the analysis is pressure and thermal stratification for storage dewars in space flight. Some assumptions are controversial but the paper presents an attempt to view the general problem.

Important references:

1. Merte, H. and Clark, J. A., J. Heat Transfer 83, 223-42 (1961).

2. Seader, J. D., Miller, W. S. and Kalvinskas, L. A., NASA CR-243 (Jun 1965).

3. Brentari, E. G. and Smith, R. V., Advan. Cryog. Eng. 10, 325-41 (1965).

4. Usiskin, C. M. and Siegel, R., J. Heat Transfer 83, No. 3, 243-53 (Aug 1961).

Key words: Boiling heat transfer; boundary effects; conduction heat transfer; convection heat transfer; film boiling; flight vehicle tankage; forced convection; gravity effects; heat flux density; heat transfer domains; laminar flow; liquid hydrogen; liquid oxygen; natural convection; nucleate boiling; pressurization failures; Rayleigh number; saturated liquid; space storage; spacecraft tankage; stratification; temperature stratification; turbulent flow; viscous flow.

PRESSURE COLLAPSE IN OXYGEN STORAGE UNDER ZERO-g
Kamat, D. V., and Abraham, W. H. (Iowa State University)
J. Spacecr. Rockets 5, No. 2, 184-8 (1968)

The authors report an analytical investigation of supercritical oxygen storage in space flight at or near zero-g 1) with fluid pressurization supplied by electric heaters, and 2) with withdrawal of oxygen from the storage dewar.

These conditions produce the possibility of pressure reduction (collapse) in the system due to large temperature gradients and consequent density gradients; differences are possible due to slow energy distribution in the fluid because essentially no natural convection occurs at or near zero-g, and the thermal conductivity of oxygen is relatively low. The collapse takes place after the density differences are created; then sudden mixing occurs as a result of fluid body forces induced, for example, by changes in the vehicle motion. The magnitude of this pressure collapse is influenced by:

1. Heater configuration. The greater the distribution of heating surfaces, the smaller the pressure reduction. Wall heaters are better than center heaters.

2. Withdrawal rate and point of withdrawal. Conducting the withdrawal process so as to induce flow in the direction of heat conduction is desirable.

3. Oxygen pressure. Higher pressures, which produce smaller density differences, are recommended.

Figures are shown for computed collapse pressures for various operating cases.

Important references:

1. Chandler, W. A., Astronaut. Aero. Eng. 1 (1963).

2. Li, T. C. H., Advan. Cryog. Eng. 7, 16-23 (1962).

Key words: Analytical model; computer program; discharge piping locations; electrical heaters; fluid mixing; heat flux density; heat transfer rates; life support systems; liquid oxygen; liquid oxygen tank; missiles and rockets; operating pressure; pressure collapse; pressure control systems; pressure decay; pressure limits; pressurization failures; safety analysis; spacecraft; spacecraft tankage; storage vessels; stratification; supercritical storage; zero-g environment; zero gravity; absorption spectra.

NONEQUILIBRIUM STORAGE AND EXPULSION OF SINGLE-PHASE CRYOGENS
Forester, C. K. (Boeing Co., Seattle, Wash.)
Advan. Cryog. Eng. 12 82-91 (1967)

Heat transfer parameters, θ (specific heat input) and Φ (energy derivitive), are illustrated for nitrogen, oxygen and parahydrogen. In a thermodynamic system in equilibrium, $\theta = -\rho(\partial H/\partial \rho)_P$ and $\Phi = (\partial P/\partial U)_\rho / \rho$. These parameters are used in the analysis of single-phase transfer of cryogenic fluids from rigid containers. In a simple equilibrium system the pressure decay rate is expressed as follows:

$$\frac{dP}{dt} = \frac{\Phi}{V} (\dot{Q}_e - \dot{\omega}_{ex} \theta)$$

where $\dot{Q}_e$ is the rate of heat added, $\dot{\omega}_{ex}$ is the expulsion rate and V is the specific volume. A simplified radial model is used in the analysis which is developed then for the nonequilibrium, nonisothermal system.

Important references:

1. Roder, H. M. and Goodwin, R. D., Nat. Bur. Stand. (U.S.) Tech. Note 130 (Dec 1961).
2. Stewart, R. B., Hust, J. G., and McCarty, R. D., Nat. Bur. Stand. (U.S.) Rept. No. 2922 (Oct 1963).
3. Strobridge, T. R., Nat. Bur. Stand. (U.S.) Tech. Note 129A (Feb 1963).
4. Johnson, V. J. (ed.), WADD Tech. Report No. 60-56 (Prepared at Nat. Bur. Stand. (U.S.), Boulder, Colo., Cryogenics Div.) (Jul 1960).
5. Woolley, H. W., Scott, R. B. and Brickwedde, F. G., J. Res. Nat. Bur. Stand. 41, 379 (Nov 1948).

Key words: Energy derivative; expulsion; expulsion rates; heat leaks; heat transfer rates; liquid hydrogen; liquid nitrogen; liquid oxygen; liquid parahydrogen; mathematical models; mixing; pressure decay; specific heat input; specific volume; storage; stratification.

THERMOPHYSICAL PROPERTIES OF OXYGEN FROM THE FREEZING LIQUID LINE TO 600°R FOR PRESSURES TO 5000 PSIA

McCarty, R. D., and Weber, L. A. (Cryogenics Division, National Bureau of Standards, Boulder, Colo.)

Nat. Bur. Stand. (U.S.) Tech. Note 384 (Jul 1971)

Included in the tables of thermophysical properties of oxygen are eight parameters that are useful in heat transfer and related calculations. They are:

Isothermal derivative, $(\partial P/\partial V)_T$

Isochoric derivative, $(\partial P/\partial T)_\rho$

Specific heat input (commonly symbolized by θ),
$V(\partial H/\partial V)_P = \rho C_p [(\partial P/\partial \rho)_T / (\partial P/\partial T)_v]$

Energy derivatives (commonly symbolized by Φ),
$V(\partial P/\partial U)_v = (V/C_v)(\partial P/\partial T)_v$

Isothermal bulk modulus (commonly symbolized by α),
$V(\partial P/\partial V)_T = -\rho(\partial P/\partial \rho)_T$

Volume expansivity (commonly symbolized by β),
$(1/V)(\partial V/\partial T)_P = (1/\rho)(\partial P/\partial T)_\rho / (\partial P/\partial \rho)_T$

Thermal diffusivity (commonly symbolized by α), $(k/\rho C_p)$

Prandtl number (commonly symbolized by Pr), $(\mu C_p/k)$

These parameters are tabulated in both the saturation table and the isobaric tables. The saturation table extends from the triple point to the critical point in 2°R increments for both liquid and vapor. The isobaric tables extend from 1 to 5000 psia in reasonably small pressure increments and from the solid phase boundary to 600°R.

Important references:

1. Sengers, J. V. and Keyes, P. H., Phys. Rev. Lett. 26, No. 2, (Jan 1971).

2. Vasserman, A. A. and Rabinovich, V. A., Thermophysical Properties of Liquid Air and its Components, Translated from Russian by Israel Program for Scientific Translations, Jerusalem (1970), available from U.S. Department of Commerce Clearinghouse for Federal Scientific and Technical Information. Springfield, Va.

3. Weber, L. A., J. Res. Nat. Bur. Stand. 74A, No. 1, 93-129, (Jan-Feb 1970).

Key words: Density; dielectric constant; enthalpy; entropy; equation of state; equation; gaseous; index of refraction; internal energy; isobar; isothermal compressibility; Joule-Thomson inversion curve; liquid; melting curve; Mollier diagram; oxygen; Prandtl number; PVT data; saturated liquid; saturated vapor; saturation properties; specific heat; storage; surface tension; tables; temperature-entropy diagram; thermal conductivity; thermal diffusivity; transportation; velocity of sound; viscosity.

ASRDI OXYGEN TECHNOLOGY SURVEY: THERMOPHYSICAL PROPERTIES OF OXYGEN
Edited by Roder, H. M. and Weber, L. A. (Cryogenics Division, National Bureau of Standards, Boulder, Colo.) NASA SP-3071, 1972

This Handbook is the result of an extensive survey of the thermophysical properties of oxygen, including densities and the thermodynamic, transport, electrical, optical, and molecular properties for the gaseous and fluid states. A thorough bibliography of published work on each property is given. Properties data are usually presented in tables, in graphs or in both. Often more than one variable is found in a particular table or graph. To present the information so that it is easy to find a particular value, the book has been arranged into three major sections. Section A contains a descriptive sheet for each property; Section B contains all the graphs; and Section C contains all the tables. The major tables cover the range 100°-600°R for pressure to 5000 psia (55-340 K, 340 atmospheres or 345 x 10^5 Pa). In addition, for property values beyond this range, recommended references are given, where available. The Handbook is designed to provide a convenient reference for the user.

Important references:

Recommended references are cited for those properties which have been critically surveyed. Other references are listed which were reviewed but not considered as basic source material.

Key words: Accommodation coefficient; compressibilities; computer programs; density; dielectric constant; diffusion; electrical conductivity; enthalpy; entropy; fixed points; free energy; gaseous oxygen; graphs; handbook thermophysical properties; heat transfer parameters; ideal gas properties; index of refraction; infrared absorption; internal energy; Joule-Thomson coefficient; latent heats; liquid oxygen; melting curve; mixture properties; oxygen; Prandtl number; property value uncertainties; PVT; solid oxygen; sound absorption; specific heats; surface tension; tables; thermal conductivity; thermal transpiration; thermodynamic diagrams; vapor pressure; velocity of sound; virial coefficients; viscosity.

THERMAL PROBLEMS PECULIAR TO CRYOGENS IN SPACE
Adelberg, M., and Schwartz, S. H. (Douglas Aircraft Co.)
Proceedings of the Aerospace Systems Conference, Los Angeles, California (Jun 27-30, 1967) Soc. Automotive Engrs., Inc., N. Y. (1967)

The authors discuss some specific thermal problems for cryogens in space flight. They are:

1. Venting problems - an all-gas vent (thermodynamic separator) is proposed which first throttles the vented fluid and then allows sufficient heat transfer from the stored fluid to the vented fluid so that only gas is finally vented.

2. Energy disturbances producing violent distortions of the liquid interface.

3. Low gravity boiling.

4. Transient times in heat transfer.

Important references:

1. Adelberg, M. and Schwartz, S. H., Advan. Cryog. Eng. 11, 568-83 (1966).

2. Siegel, R., J. Heat Transfer 86, 490-500, (1963).

3. Gebhart, B., J. Heat Transfer 85, 10 (1963).

Key words: Boiling heat transfer; boundary layers; bubble formation; gravity effects; heat exchanger; heat flux density; heat leaks; laminar flow; liquid hydrogen; liquid oxygen; meniscus; nucleate boiling; phase separation; phase separator; pressurization failures; propellant venting; spacecraft; spacecraft tankage; transient heating; turbulent flow; venting; vessels; zero gravity.

MAGNETOTHERMAL CONVECTION IN INSULATING PARAMAGNETIC FLUIDS
Carruthers, J. R., and Wolfe, R. (Bell Telephone Laboratories, Murray Hill, N. J.)
J. Appl. Phys. 39, No. 12, 5718-22 (1968)

Gaseous oxygen, a paramagnetic fluid, is, in the presence of a magnetic field, subject to a body force analogous to the body force of gravity. This magnetic body force may be equal, or greater than, that due to gravity for common magnetic fields; for example, at room temperature the gravitational and magnetic body forces are equal at a field-field gradient product of 4.8×10^6 Oe^2/cm. Both experimental and theoretical studies are reported.

Applications influenced by, or which may utilize, this phenomenon are discussed. Electrical measurements in a non-uniform magnetic field where temperature gradients exist should avoid the use of ambient oxygen or air. Magnetic pumping of paramagnetic fluids is suggested. A study of control of natural convection during crystal growth is cited. Control of natural convection for other purposes would be possible also.

Important references:

1. Resler, E. L. and Rosenweig, R. E., J. Eng. Power 89, 399 (1967).

Key words: Convection; convection heat transfer; electrical measurements; forced convection; gaseous air; gaseous nitrogen; gaseous oxygen; geometry effects; horizontal; instrumentation; magnetic effects; magnetic field gradient; magnetic pumping; natural convection; paramagnetic; vertical.

THE EVOLUTION OF CRYOGENIC STORAGE SYSTEMS TOWARD ADVANCED SPACECRAFT MISSIONS
Manatt, S. A. (The Garrett Corp., AiResearch Manufacturing Co. Division)
Proceedings of the Aerospace Systems Conference, Los Angeles, California (Jun 27-30, 1967) Soc. Automotive Engrs. Inc. N. Y. (1967)

The author describes the evolution of cryogenic storage systems for spacecraft. First there were the Gemini storage vessels characterized by supercritical fluid storage and superinsulation. Next was the Biosatellite system, which utilized the refrigeration effect of the exiting cryogen (to save insulation weight) and fluid-to-fluid heat transfer (to reduce electrical heater requirements for pressurization). Subcritical storage is discussed. Current designs, and requirements for advanced designs, are documented.

Important references:

1. Kavanagh, H. M. and Rice, P. L., National Aeronautics and Space Administration, Houston, Texas, Manned Spacecraft Center Contract No. NAS 9-1065, Final Report (1964).

Key words: Aluminum; aluminum alloy; breathing oxygen; external insulation; fill lines; flow rates; fuel cells; heat leaks; hydrogen; interface; life support system; liquid nitrogen; liquid oxygen tank; long term storage; losses; manned spacecraft; oxygen; personnel hazards; phase separation; planetary missions; portable life support systems; pressurization; simulation tests; spacecraft; subcooled storage; supercritical storage; superinsulation; tanks; two-phase; vacuum insulation; vent lines; vessels; zero-g environment; zero gravity.

FLUID DYNAMICS

REVIEW OF TWO-PHASE FLOW INSTABILITY

Bouré, J. A., Bergles, A. E., and Tong, L. S. (Centre d'Etudes Nucleaires, Grenoble, France)

Paper presented at ASME-AIChE Heat Transfer Conference, Tulsa, Okla. (Aug. 15-18, 1971)

The various flow instabilities are classified and discussed in relation to the physical mechanisms and observed effects. Mathematical analyses are summarized.

The classification "static instability" includes transitions between flow regimes or boiling modes. Changes in flow and temperature may be erratic or excursive as, for example, the Ledinegg (1954) excursion in which an unfavorable combination of pump and heated pipe pressure drop characteristic can lead to vapor-choking and exceeding of the critical boiling wall temperature. The second primary classification of "dynamic instabilities" includes all of the wave propagation phenomena, characterized by regular oscillations.

Thermal oscillations may be of acoustic frequencies, the period being about the time required for a pressure wave to travel through the system. Thurston (1967) observed these in forced flow, high flux, liquid hydrogen heat exchangers. "Density wave" or "time delay" oscillations have a period on the order of the residence time of the fluid in the system. These are slated to be the most common type of two-phase flow instability and are seen in both natural convection and forced flow systems.

This is a good review article and includes many current references. The review is quite general but lacks specific reference to liquid oxygen systems. Much of the analysis is based on non-cryogenic fluids.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 92.)

F

REVIEW OF CRITICAL FLOW RATE, PROPAGATION OF PRESSURE PULSE, AND SONIC VELOCITY IN TWO-PHASE MEDIA

Hsu, Y. Y. (National Aeronautics and Space Administration, Cleveland, Ohio, Lewis Research Center)

NASA Tech. Note D-6814 (Jun 1972)

In this report, the author summarizes the basic concepts of the field — particularly the relationships between single-phase and two-phase critical flow, and between the sonic velocity and critical flow velocity. For the single-phase case, sonic and critical velocities are essentially the same; for the two-phase case, the velocities may differ because the interface process necessary to achieve equilibrium may be slower than the rates of change of pressure in the sonic and critical flow processes.

Analytical models proposed by Fauske, Moody, Levy, and Henry are then reviewed, and those author's comparisons with experimental data are given.

The remainder of the report is devoted to analysis of the propagations of pressure pulses and waves. This represents a combination of developments by the author and reported work in the field.

The report offers minimal design-oriented conclusions or recommendations. General topics discussed are as likely to be applicable to oxygen as to other fluids.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 107.)

FLUID DYNAMICS, Chapter 5
Smith, R. V. (National Bureau of Standards, Boulder, Colo., Cryogenics Division)
Haseldon, G. G. (ed.) Cryogenic Fundamentals, Academic Press, 237-310 (1971)

The expressions for single-phase friction factor for conduits and drag coefficients for submerged bodies are developed for general fluids. A sample solution for incompressible flow in a hypothetical liquid oxygen system is given. In the experimental data which are shown for cryogenic fluids (not including oxygen), both the form and dispersion of the correlation is about the same as in normal fluids. Since the conventional correlation appears to hold even for liquids hydrogen and helium, it should also hold for the relatively conventional liquid oxygen.

In compressible flow (usually gases), the Mach number considerations of choking, subsonic, supersonic flow and shock waves are discussed. The special case of Fanno flow, i.e., steady, constant area, adiabatic, compressible flow with friction, is also discussed in terms of the ideal gas relationships. It should be cautioned that ideal gas relations are not suitable even for engineering use in and near the saturated vapor state.

Section IV of this chapter deals with flow through valves, orifices, curves, fittings, packed beds, etc. The distinguishing feature of these flows is that additional pressure losses are caused by turbulent separation and secondary flows which are not present in straight pipes. Equivalent lengths of straight pipes for various valves and fittings are tabulated as well as flow coefficients for orifices and venturis.

In two-phase flow, the momentum pressure drop due to the compressibility of the gas often is larger than the frictional pressure drop. The appropriate equation for inclusion of both momentum and frictional pressure drop is shown. When two-phase frictional pressure drop must be calculated, one normally turns to the work of Martinelli and his co-workers reported in Lockhart and Martinelli (1949) and Martinelli and Nelson (1948). Duckler, et al. (1964), in an exhaustive review study of the frictional pressure drop, have shown that the Martinelli correlation is still one of the most effective. Furthermore, almost all data for cryogenic fluids have been analyzed by use of the Martinelli approach.

The correlating curve recommended by Martinelli and Nelson (1948) is shown. This curve gives the ratio of the two-phase pressure gradient to the pressure gradient of the total flow as if it were liquid alone, as a function of a parameter, χ_{tt}. χ_{tt} contains the quality and liquid and vapor properties. Graphs have been prepared from which χ_{tt} may be read directly for oxygen, as well as for hydrogen and nitrogen. The correlations of Rogers and Tietjen (1969) for nitrogen, and Rogers (1964) for hydrogen two-phase pressure drop, modified from the Martinelli model to include the effects of pressure, are also shown.

For flow through expansions and contractions, the momentum pressure drop alone is usually considered. Expressions for expansions by Romie, et al. (1960), and for contractions by Geiger (1964) are given.

Experimental verification of these two-phase flow correlations is lacking for oxygen; however, the range of other cryogenic and non-cryogenic fluids covered is sufficiently great to justify considerable confidence in the applicability for oxygen.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A MORE SPECIFIC ABSTRACT, SEE PAGES 76, 84, 113.)

CHOKING TWO-PHASE FLOW LITERATURE SUMMARY AND IDEALIZED SOLUTIONS FOR HYDROGEN, NITROGEN, OXYGEN, AND REFRIGERANTS 12 AND 11
Smith, R. V. (National Bureau of Standards, Boulder, Colo., Cryogenics Division)
Nat. Bur. Stand. (U. S.) Tech. Note 179 (Aug 1963)

The literature summary presents a brief description and discussion of papers on choking two-phase flow. These papers are arranged with respect to analysis methods and experimental systems. The idealized solutions utilize models intended to provide upper and lower limits for the actual flow cases. Charts are presented to provide for rapid determination of choking flow for the choking point condition and for Fanno and isentropic flow for the fluids H_2, N_2, O_2, CCl_2F_2, and CCl_3F. A discussion of choking flow and relaxation phenomena is included.

A useful summary of the various models is given in tabular form. With this table and some of the explanatory material, it is often possible to decide which flow process is most applicable to the problem in question. The appropriate equations and solution charts can be located by use of the table. In calculating these charts, the author ran into difficulty with oxygen at pressures above three atmospheres because of the inconsistencies in the enthalpy and specific heat data available at that time. For that reason, the solution charts for oxygen were not carried to as high pressures as desired. Since better data is now available, e.g., McCarty and Weber (1971), these charts could be extended. [Ed. Note: The charts have been extended in an updated version of this report now in preparation by R. V. Smith].

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 108.)

CRITICAL TWO-PHASE FLOW FOR CRYOGENIC FLUIDS

Smith, R. V. (Cryogenics Division, National Bureau of Standards, Boulder, Colo.)
Randall, K. R., and Epp, R. (Wichita State University, Wichita, Kans.)

Nat. Bur. Stand. (U. S.) Tech. Note (In Press 1972)

This work presents a state-of-the-art survey intended to be useful to a designer of equipment involving two-phase flow of cryogenic fluids. It is desirable to assess the probability of critical, or choking, flow in such a system and, if possible, estimate the critical flow rate.

The literature is surveyed, primarily since Smith (1963), and the predictive results for several analytical models are evaluated and compared with experimental data. These results are discussed; however, no firm conclusions are reached because often the spread of experimental data is equivalent to the predictive results from the models.

Finally, computer evaluations are presented for oxygen, hydrogen and helium along with some design recommendations.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 109.)

FEEDLINE FLOW, Chapter 7
Fox, E. C.
Ring, E. (ed.), Rocket Propellant and Pressurization Systems, Prentice-Hall, N. J., 44-60 (1964)

This chapter considers first pressure surges due to a water-hammer type of reaction to rapid closing and opening of valves. The water-hammer analysis and solution methods are outlined for the rapid closing of valves in a moving stream. A similar analysis gives the pressure transients caused by sudden opening of valves.

Frictional pressure losses are also discussed along with pressure losses in bends, contractions, and enlargements.

The water-hammer pressure surge is an important consideration in feedlines as evidenced by the spectacular failure of the Saturn V liquid oxygen loading system (Moore and Arnold, 1968). Two-phase and cooldown surges which may also be important are not mentioned, however. Two-phase steady flow is not mentioned.

Important references:

1. Bergeron, L., Water Hammer in Hydraulics and Wave Surges in Electricity, John Wiley & Sons, Inc., New York (1961).

Key words: Contraction; cooldown; expansions; flow surges; friction factor; leakage and spills; liquid hydrogen; liquid oxygen; missiles and rockets; pressure drop; pressure surges; propellant loading systems; propellant transfer systems; Reynolds number; spacecraft; transfer line surges; transient loads; two-phase flow; valve closures; valves; water hammer.

SINGLE-PHASE TRANSFER OF LIQUEFIED GASES
Jacobs, R. B. (National Bureau of Standards, Boulder, Colo., Cryogenics Division)
Nat. Bur. Stand. (U.S.) Circular No. 596 (Dec 1958) 42 pp

The flow of cryogenic liquids through long transfer lines is analyzed. The analysis assumes that the pressure level in the line and the flow rate must be kept high enough to prevent vaporization. All of the vaporization then takes place by flashing of the liquid as it flows into the receiver vessel. The analysis assumes: steady flow, negligible gravity head, conventional friction factor-Reynolds number relationship, one-dimensional flow, and negligible effect of pressure on the liquid density and enthalpy. Factors considered are pump inefficiency, heat leak into the line, and fluid friction.

Numerical illustrations are given for calculating the minimum transfer line diameter to maintain single-phase flow for a given flow rate, insulation, length of line, and pump discharge pressure. Liquid flashing losses may also be calculated, and the effects of multiple pumping stations, cooldown, and trapped liquid losses are considered. Working curves for frictional and thermal losses are given.

Solution curves are shown for liquid oxygen and liquid hydrogen. These curves are useful for quick estimates where they are applicable. Such solutions, of course, cannot be expected to cover all possible variations of transfer lines, pumps, insulations, flow restrictions, etc. For those configurations not covered by the solution curves, this report sets down the applicable equations and illustrates the kinds of calculations which can be made.

Important references:

1. Van Gundy, D. A. and Jacobs, R. B., Advan. Cryog. Eng. 2, 156-62 (1957).

Key words: Boost pumps; cooldown; flashing; flow rates; friction; geometry effects; heat losses; insulation; liquid helium; liquid hydrogen; liquid nitrogen; liquid oxygen; long distance transfer; losses; mathematical model; NPSH; oxygen pumps; powder insulation; pressure drop; pump losses; pump speed; pumps; refrigeration; single phase flow; size effects; storage; theoretical studies; transfer piping systems; transportation; vacuum insulation; vaporization.

A NUMERICAL SOLUTION OF THE NAVIER-STOKES EQUATIONS FOR SUPERCRITICAL FLUID THERMODYNAMIC ANALYSIS

Heinmiller, P. J. (TRW Systems Group, Houston, Texas)

National Aeronautics and Space Administration, Houston, Texas, Manned Spacecraft Center Cryogenics Symposium Papers, Publ. No. MSC-04312, May 20-21, 1971, p. 131

This report is abstracted in detail under the category "Heat Transfer". The solutions of the Navier-Stokes equations by a finite difference approach, to obtain fluid convection velocity as well as temperature distributions throughout the entire fluid region (not just the boundary layer), may be of considerable interest with regard to fluid dynamics. A simulation of Apollo 12 flight data concerning stratification and pressure collapse showed good agreement.

Important references:

1. Goodrich, W. D., Texas University, Austin, Texas, Ph.D. Dissertation (May 1969).
2. Chu, C. K., ed., AIAA Selected Reprint Series 4, (Jul 1968).
3. Cheng, S. I., AIAA J. 8, No. 12 (Dec 1970).
4. Roache, P. J. and Mueller, T. J., AIAA Paper No. 68-741.
5. Wilkes, O. J. and Churchill, S. W., AIChE J. 12, No. 1 (Jan 1966).

Key words: Acceleration effects; analytical models; breathing oxygen systems; convection heat transfer; destratification; elasticity; electrical heaters; equation; gravity effects; heaters; heat leaks; life support systems; liquid oxygen; liquid oxygen tank; manned spacecraft; mathematical models; pressure collapse; pressurization; scaling laws; spacecraft tankage; storage; stratification; supercritical storage; theoretical studies; transportation; vessels; zero gravity.

CHOKED FLOW OF FLUID NITROGEN WITH EMPHASIS ON THE THERMODYNAMIC CRITICAL REGION

Hendricks, R. C., Simoneau, R. J., and Ehlers, R. C. (National Aeronautics and Space Center, Lewis Research Center, Cleveland, Ohio)

1972 Cryogenic Engineering Conference, Boulder, Colorado, Paper D-3

Experimental data for critical flow rates and pressures are presented for nitrogen, primarily in the region above the thermodynamic critical point. The authors believe their data are generally applicable to other fluids, particularly to oxygen where the properties are similar. Critical flow occurs in the region of the maximum specific heats (transposed critical) where the density changes are large. The behavior is somewhat like that for critical, two-phase flow. Data are compared with an equilibrium and a non-equilibrium (Henry and Fauske) model. The non-equilibrium model appears more appropriate at or near the two-phase region, but less appropriate in the supercritical region.

Important references:

1. Henry, R. E. and Fauske, H. K., J. Heat Transfer 93, 179 (May 1971).

2. Hsu, Y. Y., NASA-Lewis Research Center, to be published as a NASA-TN.

Key words: Critical (choking) two-phase flow; critical flow; critical pressure; critical region; liquid nitrogen; liquid oxygen; mathematical models; single-phase flow; specific heat; supercritical fluids; two-phase flow.

FLUID DYNAMICS: II. PRESSURE DROP IN SIMPLE SYSTEMS, Chapter 5
Smith, R. V. (National Bureau of Standards, Boulder, Colo., Cryogenics Division)
Haseldon, G. G. (ed.), Cryogenic Fundamentals, Academic Press, 238-43 (1971)

The expressions for single-phase friction factor for conduits and drag coefficients for submerged bodies are developed for general fluids. A sample solution for incompressible flow in a hypothetical liquid oxygen system is given. In the experimental data which are shown for cryogenic fluids (not including oxygen), both the form and dispersion of the correlation is about the same as in normal fluids. Since the conventional correlation appears to hold even for liquids hydrogen and helium, it should also hold for the relatively conventional liquid oxygen.

In compressible flow (usually gases), the Mach number considerations of choking, subsonic, supersonic flow and shock waves are discussed. The special case of Fanno flow, i.e., steady, constant area, adiabatic, compressible flow with friction, is also discussed in terms of the ideal gas relationships. It should be cautioned that ideal gas relations are not suitable even for engineering use in and near the saturated vapor state. References for compressible flow tables are cited.

Important references:

1. Shapiro, A. H., The Dynamics and Thermodynamics of Compressible Fluid Flow, Ronald Press Co., New York (1954).
2. Taylor, M. F., Int. J. Heat Mass Transfer 10, 1123-8 (1967).
3. Lindsey, W. F., NACA TR 619 (1938).

Key words: Compressible flow; drag coefficients; equations;Fanno flow; flow rates; friction factors; liquid helium; liquid hydrogen; liquid oxygen; Mach number; pressure drop; shock waves; single-phase flow; supersonic flow; velocity of sound.

PROBLEMS IN COOL-DOWN OF CRYOGENIC SYSTEMS

Bronson, J. C., Edeskuty, F. J., Fretwell, J. H., Hammel, E. F., Keller, W. E., Meier, K. L., Schuch, A. F., and Willis, W. L. (Los Alamos Scientific Laboratory, Los Alamos, New Mexico)

Advan. Cryog. Eng. 7, 198-205 (1962)

One of the main concerns of this study of the cooldown of eight and ten inch diameter stainless steel cryogenic pipelines was that stratified flow of hydrogen should not be allowed to develop. That is, flow conditions must not be such that the liquid could flow along the bottom of the pipe with relatively warm gas above. Such stratified flow could cause unequal temperature around the pipe circumference and could cause bowing of the pipeline.

Based on the earlier successful use of a correlation by Baker (1954), the same correlation was used to predict flow patterns of the eight and ten inch hydrogen lines. While the Baker correlation was originally developed for oil-gas mixtures, Bronson, et al. concluded that it is permissible to apply this correlation to the two-phase flow of hydrogen. The Baker correlation is presented as a map with coordinates related to the mass fraction of liquid and the total gas flow rate. The map is divided into regions which indicate the occurrence of dispersed flow, annular flow, bubble flow, slug flow, wave flow, plug flow, and stratified flow.

Considering the apparent wide applicability of this correlation (oil-gas mixtures, two-phase hydrogen, etc.), it would seem permissible to use the correlation for two-phase oxygen. It should be pointed out, however, that the flow patterns of such wide variety are not easy to discern, and both the original Baker diagram and the later verifications are subject to the observer's judgment. Neither are the parameters used on a firm theoretical ground; therefore, this correlation should be considered only as a rough guide for two-phase oxygen flow. No other comparable guide is known, and no oxygen two-phase flow pattern studies are known. A method of calculating cooldown time of long transfer lines is proposed and shown to produce reasonably good results with the author's data on hydrogen. This system employs a restriction at the end of the line and the calculation of the time required for critical (choking) of the escaping gas flow. The quantity of gas flow required for cooldown is computed by equating the required heat removed from the solid system to the enthalpy of vaporization of the escaping gas.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 86.)

ON TWO-PHASE HIGHLY DISPERSED FLOWS

Cumo, M., Farello, G. E., Ferrari, G., and Palazzi, G.
Comitato Nazionale per l'Energia Nucleare, Casaccia (Italy),
Centro di Studi Nucleari Lab. Rept., 18 pp

The paper presents experimental and analytical results which may be used to describe the flow patterns of some highly dispersed, turbulent two-phase flows. The flow pattern data consist primarily of the size and distribution of droplets in the dispersed flow. Some simple predictive systems are developed to describe the flows in a form useful for detailed analysis. Experimental data for freon 12 are presented, but the treatment may be applicable to all fluids. A general expression for a most probable droplet diameter and for droplet distribution is proposed.

Important references:

1. Cumo, M., Farello, G. E. and Ferrari, G., XXV Congresso Nazionale ATI, Trieste (Oct 1970).
2. Barnett, P. G., Report AEEW R 362, Winfrith, Dorchester (1964).
3. Mugele, R. A. and Evans, H. D., Ind. Eng. Chem. 43, No. 6, 1317-24 (Jun 1951).
4. Rohsenow, W. M. and Fedorovich, E., Int. J. Heat Mass Transfer 2, 683-99 (1970).

Key words: Bubble formation; burnout; critical region; droplet formation; enthalpy; entropy; freon 12; liquid oxygen; PVT data; quality; saturated liquid; size effects; storage; superheated; transportation; turbulent flow; two-phase flow; vapor pressure; velocity effects.

CRYOGENICS - FLUID STORAGE AND TRANSFER SYSTEMS, Chapter 7
Barron, R. (Louisiana Polytechnic Institute, Department of Mechanical Engineering)
Cryogenic Systems, McGraw-Hill Book Co., New York, 514-30 (1966)

Two-phase flow patterns are discussed in the terminology of Baker (1954). The Baker diagram, which maps the various flow pattern regions, is shown.

For steady flow of two-phase fluid, a special relation for low quality homogeneous flow is derived from energy considerations. For higher qualities and flow regimes other than slug or annular flow, the Lockhart-Martinelli (1949) correlation is summarized. Diabatic two-phase flow is handled by integration of local friction pressure drop over the length of lines. Momentum drop due to expansion-produced acceleration is included.

An equation for cooldown time is derived which considers steady state heat leak into the line and enthalpy changes of the solid material and fluid.

The Baker plot for two-phase flow pattern has received wide use in cryogenics. It should be pointed out, however, that the original work of Baker was carried out for the far different conditions of oil-gas mixtures. No equivalent study has been made specifically for liquid oxygen; however, some crude verifications of small regions of the map have been made for other cryogenic fluids.

The cooldown time method requires the estimation of mean flow rates and discharge gas temperature. These quantities vary in a non-linear manner during cooldown and the linear averaging procedure suggested may not be entirely adequate.

Important references:

1. Baker, O., Oil Gas J. 53, No. 12, 185-95, (1954).
2. Hatch, M. R., Jacobs, R. B., Richards, R. J., Boggs, R. N. and Phelps, G. R., Advan. Cryog. Eng. 4, 357-77 (1960).
3. Martinelli, R. C. and Lockhart, R. W., Chem. Eng. Progr. 45, No. 1, 39 (1949).
4. Martinelli, R. C. and Nelson, D. B., Trans. ASME 70, 695-702 (1948).
5. Burke, J. C., Byrnes, W. R., Post, A. H. and Ruccia, F. E., Advan. Cryog. Eng. 4, 378-94 (1960).

Key words: Bubble flow; cooldown; flow patterns; laminar flow; liquid oxygen; mist flow; plug flow; pressure drop; slug flow; stratified flow; transfer systems; turbulent flow; two-phase flow; two-phase pressure drop; wavy flow.

ANALYSIS OF FLUID CONDITIONS IN THE DISCHARGE LINE OF A CRYOGENIC CONTAINER UNDERGOING SELF-PRESSURIZED DRAINING

Campbell, Jr., H. M., and Head, R. R. (National Aeronautics and Space Administration, Huntsville, Ala., George C. Marshall Space Flight Center)

Proceedings of the American Astronautical Society Southeastern Symposium on Missiles and Aerospace Vehicles Sciences, Huntsville, Alabama (Dec. 5-7, 1966) Vol. 1

The vertically downward flow of liquid oxygen and liquid nitrogen from a self-pressurized storage tank is analyzed. The tank is self-pressurized by allowing external heat leak to bring the liquid to saturation and build up vapor pressure. As a result of the saturated condition of the stored liquid, and the reduction of static pressure as liquid incurs a velocity in the discharge line, the flow becomes two-phase in the discharge line. The quality is maximum (assuming equilibrium) at the entrance of the line and decreases due to increasing static pressure in the vertically downward flow.

Two-phase flow in the discharge line can reduce the mass capacity of the line and preclude the possibility of pumping because of the NPSH requirements of the pump. Equations are derived to express the pressure and quality as a function of container pressure, flow rate, elevation, and fluid properties. Analytical results are presented for nitrogen and oxygen and experimental results for nitrogen.

The Lockhart and Martinelli (1949) correlation for two-phase frictional pressure drop was used and the inlet pressure loss was estimated as ten percent of the velocity head. The experimental pressure drops were somewhat larger than predicted values, and the quality was slightly higher than predicted. A capacitative quality meter was mentioned but not described in detail. (Reference: Space Sciences Inc. (1964).)

The study lends support to the use of the Lockhart-Martinelli two-phase pressure drop correlation for oxygen. The slight under-prediction of two-phase pressure drop and quality may be due to neglecting the momentum pressure drop in the inlet. There was no apparent error caused by assuming thermal equilibrium.

Important references:

1. Lockhart, R. W. and Martinelli, R. C., Chem. Eng. Progr. 45, No. 1, 39 (1949).

2. Campbell, Jr., Hugh M., M.S. Thesis, Alabama University (1965).

3. Instruction Manual for the Model 206-1 Quality Measurement System, Space Sciences Inc., Document No. SSI-206-MA, Waltham, Mass., 1-7 (1964).

Key words: Aluminum; analytical model; condensation; drainage lines; equation; heating; instability; liquid nitrogen; liquid oxygen; NPSH; pressure drop; pressure surges; pressurization; propellant tanks; pumps; quality; saturated liquid; self-pressurization; spacecraft tankage; spheres; storage; tank draining; transportation; two-phase pressure drop; two-phase flow; vapor lock; vaporization; vessels.

TWO-PHASE PRESSURE DROP FOR CRYOGENIC FLUIDS
Grolmes, M. A., and Fauske, H. K.
Paper presented at the International Congress of Refrigeration, Washington, D.C. (Aug. 27 to Sep. 3, 1971)

Two-phase pressure drop correlations and experimental data for cryogenic fluids are reviewed. The Lockhart and Martinelli (1949) correlation, which probably is the most widely used, has shown only fair agreement with experiments where annular flow appears likely. A simplified annular flow correlation of Lottes and Flinn (1956), or a modification by Richardson (1958), appears to give closer agreement with the Refrigerant-11 data of Hatch and Jacobs (1962), and the nitrogen data of Shen and Jao (1969). These data probably are in the annular flow regime.

Where homogeneous two-phase flow is likely, the homogeneous flow correlation of Lottes and Flinn (1956) gives much closer agreement with experimental data than either the Martinelli correlation or the Lottes and Flinn (1956) annular flow correlation. These data of de La Harpe (1969) for helium I, and Sugden and Timmerhaus (1969) for Refrigerant-11 were indicated by the Baker (1954) flow regime map to lie within the homogeneous flow region.

It should be pointed out that Shen and Jao (1970), in their paper, attributed their disagreement with the Martinelli correlation to experimental errors. Rogers and Tietjen (1969) concluded from two-phase nitrogen experiments that the Martinelli correlation was applicable and not dependent on the flow pattern.

Important references:

1. Lockhart, R. W. and Martinelli, R. C., Chem. Eng. Progr. 45, 39 (1949).
2. Martinelli, R. C. and Nelson, D. B., Trans. ASME 70, 695 (1948).
3. Hatch, M. R. and Jacobs, R. B., A.I.Ch.E. J. 8, 18 (1962).
4. Richards, R. J., Stewart, W. G. and Jacobs, R. B., Advan. Cryog. Eng. 5, 103-10 (1960).
5. Shen, P. S. and Jao, Y. W., Advan. Cryog. Eng. 15, 378 (1969).
6. de La Harpe, A., et al., Advan. Cryog. Eng. 14, 170 (1969).
7. Lapin, A. and Bauer, E., Advan. Cryog. Eng. 12, 409-19 (1967).
8. Lottes, P. A. and Flinn, W. S., Nucl. Sci. Eng. 1, 461 (1956).
9. Baker, O., Oil Gas J. 53, No. 12, 185 (1954).
10. Leonhard, K. E. and McMordie, R. K., Advan. Cryog. Eng. 6, 481 (1961).

Key words: Annular flow; density; flow patterns; freon 11; homogeneous flow; liquid helium; liquid hydrogen; liquid nitrogen; pressure drop; size effects; two-phase; two-phase flow; two-phase pressure drop; viscosity.

G

TWO-PHASE FRICTION FACTOR FOR NITROGEN BETWEEN ONE ATMOSPHERE AND THE CRITICAL PRESSURE

Rogers, J. D., and Tietjen, G. (Los Alamos Scientific Laboratory, Los Alamos, New Mexico)

A.I.Ch.E. J. 15, No. 1, 144-6 (Jan 1969)

The two-phase pressure drop correlation of Martinelli, et al. (1944) has been shown by Wicks, et al. (1964) to be able to correlate a broad spectrum of data. Bartlit and Williamson (private communication with Rogers) concluded that the Martinelli model was not dependent on the flow pattern, except that annular flow appeared to produce slightly higher pressure drops than other flow patterns. For these reasons, the Martinelli model was used to predict the two-phase pressure drop of nitrogen.

The effect of elevated pressures, up to the critical pressure, was considered. By computing the values and pressure derivatives of the Martinelli parameters at one atmosphere and the critical pressure, the values at intermediate pressures were estimated and an empirical equation derived. The equation has the correct single-phase and critical point limiting values for the parameters.

The pressure dependent correlation was derived specifically for nitrogen. In previous works, Rogers (1964, 1968) had derived similar expressions for hydrogen. As the author comments, the nitrogen correlation is probably usable for oxygen, but it would appear that a generalized correlation in terms of reduced pressures should be possible.

Important references:

1. Lockhart, R. W. and Martinelli, R. C., Chem. Eng. Prog., 45, 39 (1949).
2. Martinelli, R. C., Boelter, L. M. K., Taylor, T. H. M., Thomsen, E. G. and Morrin, E. H., Trans. Amer. Soc. Mech. Eng. 66, 139 (1944).
3. Martinelli, R. C. and Nelson, D. B., Trans. Amer. Soc. Mech. Eng. 70, 695 (1948).
4. Rogers, J. D., Advan. Cryog. Eng. 9, 311 (1964).
5. Rogers, J. D., A.I.Ch.E. J. 14, 895 (1968).
6. Wicks, M., Dukler, A. E. and Cleveland, R. G., A.I.Ch.E. J. 10, 38 (1964).

Key words: Equations; flow patterns; friction factor; gaseous air; gaseous nitrogen; gaseous oxygen; liquid air; liquid nitrogen; liquid oxygen; Martinelli models; pressure drop; two-phase; two-phase flow; two-phase pressure drop.

PRESSURE DROP OF TWO-PHASE FLOW IN A PIPELINE WITH LONGITUDINAL VARIATIONS IN HEAT FLUX

Shen, P. S., and Jao, Y. W. (Toronto University, Toronto, Ontario, Canada)

Advan. Cryog. Eng. 15, 78-81 (1970)

Pressure drop in two-phase nitrogen flow with heat transfer was investigated. Due to vaporization, the momentum pressure drop is usually appreciable in systems with simultaneous two-phase flow and heat transfer. The frictional part of the pressure drop was calculated by means of the Martinelli-Nelson (1948) correlation. The pressure drop parameter, φ, of this correlation is the ratio of two-phase pressure drop to the pressure drop if the flow were totally liquid.

The measured values of φ presented in graphical form appear to fall 20 to 60 percent below the Martinelli-Nelson recommended curve; the larger deviations occurred at lower quality. The author believes a major cause of the discrepancy was inaccuracy in the measurement of quality and an inadequate averaging procedure. The effect of non-uniform heat flux was not discernible.

Of the cryogenic fluids, liquid nitrogen has properties closest to liquid oxygen so that conclusions as to the applicability of the Martinelli-Nelson correlation should be transferrable. The rather poor correlation obtained in this study appears to be due largely to experimental problems rather than inapplicability of the correlation.

Important references:

1. Lockhart, R. W. and Martinelli, Chem. Eng. Progr. 45, 39 (1949).
2. Martinelli, R. C. and Nelson, D. B., Trans. ASME 70, No. 8, 695 (1948).
3. Hatch, M. R., Jacobs, R. B., Richards, R. J., Boggs, R. N. and Phelps, G. R., Advan. Cryog. Eng. 4, 357 (1960).
4. Hatch, M. R. and Jacobs, R. B., A.I.Ch.E. J. 8, No. 1, 18 (1962).
5. Richards, R. J., Steward, W. G. and Jacobs, R. B., Advan. Cryog. Eng. 5, 103 (1960).

Key words: Frictional pressure drop; Martinelli-Nelson correlation; momentum pressure drop; nitrogen; non-insulated; pipe lines; piping insulation; pressure drop; pumps pipings and fittings; two-phase; two-phase pressure drop; two-phase flow.

FLUID DYNAMICS: VB. TWO-PHASE PRESSURE DROP, Chapter 5
Smith, R. V.
Haselden, G. G. (ed.), Cryogenic Fundamentals, Academic Press, New York, 269-83 (1971)

In two-phase flow, the momentum pressure drop due to the compressibility of the gas often is larger than the frictional pressure drop. The appropriate equation for inclusion of both momentum and frictional pressure drop is shown. When two-phase frictional pressure drop must be calculated, one normally turns to the work of Martinelli and his co-workers reported in Lockhart and Martinelli (1949) and Martinelli and Nelson (1948). Duckler, et al. (1964), in an exhaustive review study of the frictional pressure drop, have shown that the Martinelli correlation is still one of the most effective. Furthermore, almost all data for cryogenic fluids have been analyzed by use of the Martinelli approach.

The correlating curve recommended by Martinelli and Nelson (1948) is shown. This curve gives the ratio of the two-phase pressure gradient to the pressure gradient of the total flow as if it were liquid alone, as a function of a parameter, χ_{tt}. χ_{tt} contains the quality and liquid and vapor properties. Graphs have been prepared from which χ_{tt} may be read directly for oxygen, as well as for hydrogen and nitrogen. The correlations of Rogers and Tietjen (1969) for nitrogen, and Rogers (1964) for hydrogen two-phase pressure drop, modified from the Martinelli model to include the effects of pressure, are also shown.

For flow through expansions and contractions, the momentum pressure drop alone is usually considered. Expressions for expansions by Romie, et al. (1960), and for contractions by Geiger (1964) are given.

Experimental verification of these two-phase flow correlations is lacking for oxygen; however, the range of other cryogenic and non-cryogenic fluids covered is sufficiently great to justify considerable confidence in the applicability for oxygen.

Important references:

1. Dukler, A. E., Wicks (III), M. and Cleveland, R. G., A.I.Ch.E. J. 10, 38-43; 44-51 (1964).
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Key words: Contractions; cooldown; critical (choking) two-phase flow; expansions; flow patterns; instability; liquid hydrogen; liquid nitrogen; liquid oxygen; mass-limiting flow; pressure drop; pressure oscillations; quality; two-phase flow; two-phase pressure drop.

CRYOGENICS — FLUID STORAGE AND TRANSFER SYSTEMS, Chapter 7
Barron, R. (Louisiana Polytechnic Institute, Department of Mechanical Engineering)
Cryogenic Systems, McGraw-Hill Book Co., New York, 514-30 (1966)

Two-phase flow patterns are discussed in the terminology of Baker (1954). The Baker diagram, which maps the various flow pattern regions, is shown.

For steady flow of two-phase fluid, a special relation for low quality homogeneous flow is derived from energy considerations. For higher qualities and flow regimes other than slug or annular flow, the Lockhart-Martinelli (1949) correlation is summarized. Diabatic two-phase flow is handled by integration of local friction pressure drop over the length of lines. Momentum drop due to expansion-produced acceleration is included.

An equation for cooldown time is derived which considers steady state heat leak into the line and enthalpy changes of the solid material and fluid.

The Baker plot for two-phase flow pattern has received wide use in cryogenics. It should be pointed out, however, that the original work of Baker was carried out for the far different conditions of oil-gas mixtures. No equivalent study has been made specifically for liquid oxygen; however, some crude verifications of small regions of the map have been made for other cryogenic fluids.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A MORE DETAILED ABSTRACT, SEE PAGE 79.)

PROBLEMS IN COOL-DOWN OF CRYOGENIC SYSTEMS

Bronson, J. C., Edeskuty, F. J., Fretwell, J. H., Hammel, E. F., Keller, W. E., Meier, K. L., Schuch, A. F., and Willis, W. L. (Los Alamos Scientific Laboratory, Los Alamos, New Mexico)

Advan. Cryog. Eng. 7, 198-205 (1962)

One of the main concerns of this study of the cooldown of eight and ten inch diameter stainless steel cryogenic pipelines was that stratified flow of hydrogen should not be allowed to develop. That is, flow conditions must not be such that the liquid could flow along the bottom of the pipe with relatively warm gas above. Such stratified flow could cause unequal temperature around the pipe circumference and could cause bowing of the pipeline.

Based on the earlier successful use of a correlation by Baker (1954), the same correlation was used to predict flow patterns of the eight and ten inch hydrogen lines. While the Baker correlation was originally developed for oil-gas mixtures, Bronson, et al. concluded that it is permissible to apply this correlation to the two-phase flow of hydrogen. The Baker correlation is presented as a map with coordinates related to the mass fraction of liquid and the total gas flow rate. The map is divided into regions which indicate the occurrence of dispersed flow, annular flow, bubble flow, slug flow, wave flow, plug flow, and stratified flow.

Considering the apparent wide applicability of this correlation (oil-gas mixtures, two-phase hydrogen, etc.), it would seem permissible to use the correlation for two-phase oxygen. It should be pointed out, however, that the flow patterns of such wide variety are not easy to discern, and both the original Baker diagram and the later verifications are subject to the observer's judgment. Neither are the parameters used on a firm theoretical ground; therefore, this correlation should be considered only as a rough guide for two-phase oxygen flow. No other comparable guide is known, and no oxygen two-phase flow pattern studies are known. A method of calculating cooldown time of long transfer lines is proposed and shown to produce reasonably good results with the author's data on hydrogen. This system employs a restriction at the end of the line and the calculation of the time required for critical (choking) of the escaping gas flow. The quantity of gas flow required for cooldown is computed by equating the required heat removed from the solid system to the enthalpy of vaporization of the escaping gas.

Important references:

1. Baker, O., Oil Gas J. (Jul 1954).

Key words: Annular flow; bending; bowing; bubble flow; cool-down; cooldown time; critical (choking) two-phase flow; dispersed flow; enthalpy; flow rates; gaseous hydrogen; gaseous oxygen; heat of vaporization; liquid hydrogen; liquid oxygen; pipe lines; plug flow; pressure oscillations; pumps pipings and fittings; slug flow; stratification; stratified flow; temperature profiles; temperature stratification; two-phase flow; wave flow.

COOLDOWN OF LARGE-DIAMETER LIQUID HYDROGEN AND LIQUID OXYGEN LINES

Commander, J. C., and Schwartz, M. H. (Aerojet-General Corporation, Sacramento, California)

NASA CR 54809, AGC 8800-54 (Prepared for NASA by Aerojet General Corp. under Contract NAS 3-2555) (Apr 1966) 54 pp

Theoretical analyses of the cooldown of large liquid hydrogen and liquid oxygen transfer lines are reported in addition to experimental observations for liquid hydrogen and limited experimental results for liquid nitrogen. Of primary concern were the thermal stresses which could be caused by temperature gradients in the line. Bowing and longitudinal stresses in the pipeline and hoop stresses in large flanges were investigated.

Various cooldown techniques were considered:

(1) Cooldown with liquid nitrogen. Advantages would be gained in liquid cost and ease of handling, but not with respect to thermal stresses.

(2) Pumping liquid hydrogen or liquid oxygen directly into the warm system at a rate sufficiently high to prevent stratification. This procedure, while it reduces the tendency for bowing, causes rapid cooling and large hoop stresses in the flanges.

(3) Atomization stations.

(4) An internal sparging line to inject spray. Expense, pressure drop, and maintenance difficulty were cited as objections to these methods.

(5) Precooling with boil-off gas was selected as the most appealing approach to cooldown, since temperature gradients during gas precooling are low.

The theoretical analysis was based on the gas precooling method, and was carried out by analog computer. The critical hoop stresses in the flanges were calculated for cold shocking after successively greater amounts of precooling until that precooling temperature was found at which the hoop stress was less than the metal yield strength. A precooling temperature of 360 °R was found to be sufficiently low to allow introduction of liquid oxygen.

The experimental data obtained at the Aerojet facility did not include liquid oxygen measurements due to lack of funds for the project. Nor were the flow measurements made which were necessary for comparison of experiments with theoretical calculations for the liquid nitrogen tests which were run. The analysis was based on an assumed fixed flow rate during cooldown; whereas, in actual practice, the flowrate is known to vary significantly from a minimum at the beginning of cooldown when the transfer line contains mostly gas, to a maximum as the pipe fills with liquid.

Important references:

1. Aerojet-General Report No. 153:R102 (with Supplements 1, 2, and 3) (Jan 1964).

Key words: Analog; boil-off gases; bowing; chilldown; cooldown; cooling procedures; flanged joint; flanges; liquid hydrogen; liquid nitrogen; liquid oxygen; materials failure; mathematical model; missiles and rockets; rocket engine test stands; standard operating procedures; storage; theoretical studies; thermal contractions; thermal stresses; transfer lines; transfer piping systems; transient loads; transportation; turbopumps; vacuum insulated pipes.

LIQUID REQUIREMENTS FOR THE COOL-DOWN OF CRYOGENIC EQUIPMENT

Jacobs, R. B. (National Bureau of Standards, Boulder, Colo., Cryogenics Division)

Advan. Cryog. Eng. 8, 529-35 (1963)

Relations are derived to estimate the amount of cryogenic liquid required to cool a piece of equipment from room temperature down to the liquid temperature or to some intermediate temperature. The computed results are presented in convenient graphical form with separate curves for stainless steel, aluminum, and copper. A separate graph is presented for liquid oxygen as well as helium, hydrogen, and nitrogen.

Two limiting cases are computed: the first is the minimum liquid requirement which is achieved when all of the possible refrigeration capacity of the liquid is utilized, i.e., when the boil-off gas is discharged at the temperature of the metal being cooled. The second limiting case, the maximum liquid requirement, is considered to occur when all of the latent heat of the liquid is utilized but none of the sensible heat of the vapor, i.e., saturated vapor is discharged. It is pointed out that the amount of liquid designated as "maximum" might be exceeded if liquid were discharged out the vent. This condition should be preventable, however.

This report provides an extremely easy method of estimating liquid requirements for cooldown. Of course, actual requirements would lie somewhere between the minimum and maximum values presented, but to determine accurately where between these limits the true solution lies is orders of magnitude more difficult. In most cases, it would seem worth the effort. A useful rule of thumb might be: cooldown processes resembling "submersion" cooling, i.e., cooling of a body surrounded by liquid, would tend toward the maximum liquid requirement; cooling of conduits of large length-to-diameter ratio would tend toward the minimum liquid requirement.

Key words: Aluminum; cooldown; cooldown equipments; copper; fill lines; fluid requirements; heat of vaporization; liquid helium; liquid hydrogen; liquid nitrogen; liquid oxygen; liquid oxygen tank; metals; missiles and rockets; piping; pumps; saturated liquid; specific heat; stainless steel; storage; theoretical studies; transfer lines; transportation.

A COMPARISON OF COOLDOWN TIME BETWEEN INTERNALLY COATED AND UNCOATED PROPELLANT LINES

Leonhard, K. E., Getty, R. C., and Franks, D. E. (General Dynamics/Convair, San Diego, California)

Advan. Cryog. Eng. 12, 331-9 (1967)

The duration of film boiling during cooldown can be shortened by applying a low conductivity layer of material to the inner surface of a transfer line. The insulating effect of this layer results in a large temperature difference across the layer and a reduced temperature of the surface in contact with the boiling liquid. Thus, nucleate boiling with its characteristically high heat flux is achieved earlier in the cooldown process. Cooldown time is thereby shortened.

Ten mil layers of fluorocarbon plastic were applied inside 2-inch diameter, 3-foot long stainless steel tubes. Wall temperatures were recorded during cooldown. Cooldown times were reduced considerably by the coatings (apparently by as much as 50 percent). The cooling rates of the coated lines were practically unaffected by the coolant flow rate, and the wall temperatures dropped smoothly. In uncoated lines the cooling rate was a strong function of flow rate and the temperature dropped first gradually, then sharply at the onset of nucleate boiling.

The cooldown of a very short pipe, such as studied here, like the cooling of submerged bodies, could be classified as heat transfer-limited cooldown. It should be pointed out that the cooling of even moderately long pipelines is limited, not by the rate of heat transfer, but mostly by the rate at which boil-off gas can be exhausted. This gas flow-limited cooldown would be influenced very little by changes in the inside heat transfer coefficient. In fact, successful transfer line cooldown time prediction models have assumed effectively infinite heat transfer coefficient.

There is a possibility, however, that such coatings might be beneficial to the surging problem. One cause of surging is a delay in the production of gas which, in turn, allows an excessive inflow of liquid at the start of cooldown. This excessive liquid in the warm pipe sometimes erupts into vapor almost explosively creating a large pressure surge. An insulating coating might prevent the delay in build-up of back pressure and thus promote a steady inflow of liquid.

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Key words: Boiling heat transfer; coatings; cooldown; film boiling; flow effects; flow surges; internal insulation; Kel-F; liquid nitrogen; nucleate boiling; piping; propellant transfer systems; size effects; stainless steel; storage; transfer line surges; transfer lines; transportation.

COOLDOWN TRANSIENTS IN CRYOGENIC TRANSFER LINES

Steward, W. G., Smith, R. V., and Brennan, J. A. (National Bureau of Standards, Boulder, Colo., Cryogenics Division)

Advan. Cryog. Eng. 15, 354-63 (1970)

Results of cooldown experiments with liquid nitrogen and liquid hydrogen in a 200 foot test transfer line were analyzed. The mathematical model depicts the liquid and vapor streams as being divided into finite particles whose individual fluctuations are followed. A computer solution produces time and space variations of all the variables. Pressure surges of at least seven times the inlet pressure and flow reversals fifteen times the steady forward flow were recorded and calculated.

A highly simplified liquid-warm gas model was used for a cooldown time prediction method. Dimensionless cooldown time parameters can be read from a graph of generalized solutions. This simplified model is applicable to systems with relatively large length-to-diameter ratios; the exact limitation on L/D was not determined but predictions were adequate down to L/D of 480. This method has been used successfully to predict cooldown time of large liquid oxygen supply lines associated with the Saturn V booster. The method would not work for submersion cooling of solid bodies.

The full computer program provides detailed predictions of the variables but computer time is very significant. Adaptation to complex geometry requires either the contriving of an equivalent straight uniform pipeline or internal modifications in the program. A simplified program for prediction of the initial cooldown surges also has been developed by Steward (1965). This method underpredicted liquid hydrogen surges in the NBS tests but it is possible that further testing would have demonstrated closer agreement; it did correctly predict the liquid nitrogen surges and the Saturn V oxygen supply line surges.

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Key words: Analytical model; boiling heat transfer; computer program; cooldown; flow rates; launch facilities; launch vehicles; liquid hydrogen; liquid nitrogen; liquid oxygen; missiles and rockets; oscillations; pressure surges; pumps pipings and fittings; saturated liquid; subcooled fluid; transfer line surges; transfer lines; transient heating; two-phase; wall temperature.

A STUDY OF LC-39 CRYOGENIC SYSTEMS — FINAL REPORT. PART II COOLDOWN PRESSURE SURGES

Voth, R. O. (Part II) (National Bureau of Standards, Boulder, Colo., Cryogenics Division)

Nat. Bur. Stand. unpublished report (Sep 1971)

A study has been conducted of the pressure and flow surges generated during cooldown of a 14 inch diameter, 1600 ft. liquid oxygen transfer line at Kennedy Space Center, Florida. The purpose of the study was to determine if the surges currently being measured could be predicted by a simplified mathematical model (Steward, 1964) and to determine from the model if damaging pressure surges may be present at other points than the measurement points. Also, if the model proved successful it could be used to predict the effects of changes in cooldown procedure without the expense of experiments. A second mathematical model was developed for the prediction of cooldown time including the effect of external heat leak to the uninsulated lines from the surroundings.

The Kennedy liquid oxygen system has a complexity of valves, filters, a pump, and a reduction of pipe size toward the discharge end. Since the original models did not allow for these complexities, it was necessary to devise equivalent simple systems for computational purposes. Due to the location of the pump and a check valve, it was necessary to divide the solution into the lengths of pipe upstream and downstream from the check valve. The solutions for the downstream part were considered to be in sufficient agreement with the observed surges to use the model for untried conditions. In the upstream region a pressure spike had been observed which did not appear in the computed pressure history. This spike was shown to be due to a water hammer effect which could not be predicted by the model. Heat transfer rate from the ambient air, which is involved in the cooldown time calculation, is difficult to determine. Since this value could only be estimated, cooldown time for various heat transfer rates was calculated to show their effect.

As a result of this study various procedure changes to shorten cooldown time were recommended. It was concluded that no damaging pressure surges would result.

The inability of the surge model to predict the water hammer type of pressure spike is a definite shortcoming. The author recommends further work to extend the surge model appropriately.

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Key words: Check valves; computer programs; cooldown; filters; flow surges; ground support equipment; heat leaks; instability; launch facilities; launch vehicles; liquid oxygen; mathematical models; missiles and rockets; predictive methods; pressure surges; propellant loading systems; propellant transfer systems; pumps; size effects; transfer line surges; uninsulated lines; valves; water hammer.

REVIEW OF TWO-PHASE FLOW INSTABILITY

Boure, J. A., Bergles, A. E., and Tong, L. S. (Centre d'Etudes Nucleaires, Grenoble, France)

Paper presented at ASME-AIChE Heat Transfer Conference, Tulsa, Okla (Aug 15-18, 1971)

The various flow instabilities are classified and discussed in relation to the physical mechanisms and observed effects. Mathematical analyses are summarized.

The classification "static instability" includes transitions between flow regimes or boiling modes. Changes in flow and temperature may be erratic or excursive as, for example, the Ledinegg (1954) excursion in which an unfavorable combination of pump and heated pipe pressure drop characteristic can lead to vapor-choking and exceeding of the critical boiling wall temperature. The second primary classification of "dynamic instabilities" includes all of the wave propagation phenomena, characterized by regular oscillations.

Thermal oscillations may be of acoustic frequencies, the period being about the time required for a pressure wave to travel through the system. Thurston (1967) observed these in forced flow, high flux, liquid hydrogen heat exchangers. "Density wave" or "time delay" oscillations have a period on the order of the residence time of the fluid in the system. These are slated to be the most common type of two-phase flow instability and are seen in both natural convection and forced flow systems.

This is a good review article and includes many current references. The review is quite general but lacks specific reference to liquid oxygen systems. Much of the analysis is based on non-cryogenic fluids.

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21. Vernier, P. and Delhyye, J. M., Rev. Energ. Primaire 4, No. 1-2 (1968).

Key words: Boiling regime transitions; critical (choking) two-phase flow; dynamic instabilities; flow excursions; flow instability; flow regime transitions; fluid oscillations; forced flow; frequency effects; geometry effects; instability; liquid hydrogen; liquid oxygen; natural convection; pressure drop; pressure oscillations; static instabilities; thermal oscillations; two-phase flow; vapor formation; wall temperatures.

STABILITY INVESTIGATION OF THERMALLY INDUCED FLOW OSCILLATIONS IN CRYOGENIC HEAT EXCHANGERS

Friedly, J. C., Manganaro, J. L., and Kroeger, P. G. (General Electric Company, Schenectady, N. Y., Research and Development Center)

National Aeronautics and Space Administration, Huntsville, Ala. George C. Marshall Space Flight Center Final Rept. Contract No. NAS 8-21045 (Oct 1967)

Liquid oxygen flow oscillation data of NASA (Fleming and Staub 1966) and hydrogen data of Thurston (1966) were compared with a stability analysis of an analytical model of the systems. The model is based on an original model of Zuber (1966) with added dynamic heat transfer from the wall. Stability is determined by use of the Nyquist stability criterion. Both a full analytical solution and a simplified criterion were developed. The criterion includes the effect of upstream and downstream pressure drop as well as acceleration and friction pressure drops.

The predictions tended to be slightly more unstable than the experimental systems; however, these deviations apparently are within the imprecision of the model and the data. Application of this model to practical systems with more complicated geometry would require considerable modification. As with other stability criteria, this method does not predict the amplitude of oscillations.

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9. Thurston, R. S., Paper presented at the Cryogenic Engineering Conference, Stanford, California, August 1967; also Los Alamos Scientific Laboratory Report No. LA-DC 8587 (Aug 1967).

Key words: Analytical model; equations; fluid oscillations; heat exchangers; heat transfer coefficient; heat transfer equipment; instability; liquid hydrogen; liquid oxygen; mathematical models; Nyquist criterion; pressure drop; pressure oscillations; stability analyses; stability criteria.

COOLING OF CRYOGENIC LIQUIDS BY GAS INJECTION

Larsen, P. S., and Clark, J. A. (Michigan University, Ann Arbor, Michigan)

Advan. Cryog. Eng. 8, 507-20 (1963)

This report presents an analysis of the subcooling of liquid oxygen in pump suction lines by means of helium gas injection. The paper deals primarily with heat transfer and thermodynamics, and is abstracted in greater detail under the category of "Heat Transfer". Overlapping into fluid dynamics is apparent since bubble dynamics plays an essential role in the analysis. Bubble rise velocity enters into the gas hold-up time; thus, bubble terminal velocity, mutual interference, and coalescence are discussed, as are the possibilities of geysering and liquid hammer effects.

Key words: Cooling; fill lines; friction; gas bubbles; gas injection; helium; injection cooling; liquid oxygen; mathematical model; nitrogen; piping; pumps; simulation tests; size effects; solubility; spacecraft tankage; storage; subcooling; theoretical studies; transportation.

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FAILURE OF APOLLO SATURN V LIQUID OXYGEN LOADING SYSTEM
Moore, W. I., and Arnold, R. V. (National Aeronautics and Space Administration, Kennedy Space Center, Florida, John F. Kennedy Space Center)
Advan. Cryog. Eng. 13, 534-44 (1966)

The rupture of an 18 inch flexible hose feeding a 10,000 gpm liquid oxygen pump resulted in the spillage of more than 700,000 gallons of liquid oxygen at Kennedy Space Center, Florida. Additional damage was caused to the storage tank when the ullage pressure dropped below atmospheric due to the rapid draining and shut-off of replenishment gas. The negative pressure differential caused a partial collapse of the storage inner vessel.

The cause of the line rupture was traced to a water hammer effect in a pneumatically operated butterfly valve. As the valve first began to open, the trapped gas in the line escaped at high velocity. The liquid which followed the gas impacted against the partially open valve disk and, due to the off center position of the pivot, forced the valve to close. The resulting deceleration of the liquid could have produced a pressure exceeding 3700 psi which is above the rupture limit of the flex hose. Investigation uncovered several other sources of water hammer in the liquid oxygen system.

The repair of the supply tank by internal hydraulic pressure was described. Modifications in the system and operating procedures included installation of bypass lines in order to pre-chill and fill the lines with liquid and replacement of a manually operated valve with a remotely operated valve for emergency shut-off.

This report provides many object lessons for designers of future systems.

Key words: Accident analysis; accident investigations; by-pass lines; carbon steel; cooldown; cracks; flexible piping; flow surges; hydrostatic reforming; hydrostatic testing; instability; launch facilities; leakage and spills; liquid oxygen; missiles and rockets; operation irregularities; pipe line design; pipe line ruptures; piping system damages; piping systems; pressure rise; pressure surges; remote operation systems; spacecraft; storage; storage tanks; storage vessels; transfer line surges; transfer lines; vacuum relief valves; valve failures; valves and controls; vessels; water hammer.

ELIMINATION OF THE GEYSERING EFFECT IN MISSILES
Morgan, S. K., and Brady, H. F. (Martin Company, Denver, Colo.)
Advan. Cryog. Eng. 7, 206-13 (1962)

The geysering in liquid oxygen feed lines 7 inches in diameter and 237 inches long is discussed. The dynamics of bubble formation and motion are essential to the understanding of the geysering phenomenon. Small concentrations of bubbles tend to rise independently, but as the bubble population increases the bubbles begin to interact. Thus, the leading bubbles create a wake which causes the following bubbles to accelerate toward the leading bubbles. This leads to "swarming" or coalescence of vapor, a slowing of the rise, reduction of static pressure below the bubble, increased vaporization rate, etc., until finally the geysering takes place.

Nine approaches to reduction or elimination of geysering are listed. The approaches discussed in some detail are helium injection, topping with subcooled liquid, and cross-feed recirculation. The last method appears to have the fewest disadvantages.

This report gives a clear picture of the mechanism involved in geysering. Some useful quantitative results are presented relative to topping temperature and flow rate. Recirculation characteristics presented appear to be relevant only to the particular system tested, however.

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Key words: Bubble dynamics; cross-feed recirculation; cross connections; flow instability; flow rates; fluid dynamics; gas injection; gaseous helium; geysering; leakage and spills; liquid oxygen; missiles and rockets; propellant transfer systems; propellants systems; recirculation; recommended practices; storage; subcooled propellants; topping; transportation; transfer lines; vertical.

AN EXPERIMENTAL INVESTIGATION OF GEYSERING IN VERTICAL TUBES
Murphy, D. W. (Martin Company, Denver, Colo.)
Advan. Cryog. Eng. 10, 353-9 (1965)

Geysering is the expulsion of a liquid from a vertical tube or vessel due to rapid accumulation of vapor in the liquid column. A consequence of geysering is impact loading on the bottom of the tube when the liquid falls back. The resulting pressure spike can cause serious failures and spillages. The heat absorbed by a vertical cryogenic transfer line is carried upward by natural convection currents until the upper part of the liquid column becomes saturated. As bubbles form due to further heating they may tend to coalesce into a larger "Taylor Bubble" which causes a pressure reduction below due to buoyancy and expulsion of liquid. Further evaporation may then occur. Under certain conditions of heat flux, geometry and fluid properties, the process becomes unstable and geysering results.

Experimental data were gathered for a variety of tubes and for the fluids water, freon, and liquid nitrogen. Heat flux was supplied through ambient heating through foam insulation, radiant heating, and electric blanket heaters. Several correlating methods were tried and finally a successful pair of correlating parameters were found whereby the non-geysering or geysering tendency of the test runs were predicted.

The correlation appears to produce a remarkably sharp demarcation between geysering and non-geysering conditions. The absence of apparently pertinent properties, such as heat of vaporization, liquid-to-vapor density ratio, etc., from the correlations possibly indicates caution is advisable in extending the correlation to an untried fluid such as liquid oxygen. The success with the widely different fluids used does seem encouraging, however.

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Key words: Bubble formation; drainage lines; equation; freon; freon 113; geometry effects; geysering; heat flux density; insulation; leakage and spills; line rupture; liquid hydrogen; liquid nitrogen; liquid oxygen; missiles and rockets; natural convection; Nusselt number; pressure surges; propellant feed lines; propellants; propellant tanks; Rayleigh number; Reynolds number; size effects; spacecraft; spacecraft tankage; storage; transportation; tubes; water.

SATURN BOOSTER LIQUID OXYGEN HEAT EXCHANGER DESIGN AND DEVELOPMENT
Platt, G. K., and Wood, C. C. (National Aeronautics and Space Administration, Huntsville, Ala., George C. Marshall Space Flight Center)
Advan. Cryog. Eng. 7, 296-302 (1962)

Liquid oxygen tank pressurization for the Saturn booster is achieved by evaporation of liquid oxygen from the main pump discharge of each engine. The development of a heat exchanger to satisfy the pressurization requirements for two different engine thrust levels, while operating at a steady flow rate and pressure, is the subject of this report.

A gas generator was tested under simulated operating conditions. Pressure oscillations as much as 300 psi above and below the mean of about 500 psi, with a frequency of about 1/3 cps, were observed. The liquid oxygen flow rate sometimes stopped entirely during pressure peaks. These oscillations decreased and finally became insignificant as carbon built up and decreased the heat transfer coefficient on the hot-gas side of the heat exchanger. Conclusions were that oscillations were aggravated by high heat transfer coefficient. Other destabilizing factors were low flow rates and short single-phase liquid zone ahead of the boiling zone.

A cavitating venturi in the liquid oxygen entrance effectively stopped the oscillations. Another remedy was a tar-like coating applied to the outside surface of the coils to spoil the heat transfer coefficient. A simple stability threshold chart was devised.

The conclusions regarding destabilizing influences are in agreement with the more recent generalized analyses of Bouré (1966) and others. Severity of these measured oscillations emphasizes the need for continued studies in this field. The generalized analyses are essential for prediction of operating characteristics, but the specific experimental data such as presented here are equally essential in verifying the analyses.

Important references:

1. Kays, W. M. and London, A. L., Compact Heat Exchangers, National Press (1955).
2. Gram, A. J., Mackey, C. O. and Monroe, E. S., ASME Paper 56-A-127.
3. Sutton, G. P., Rocket Propulsion Elements, John Wiley and Sons, Inc., New York (1958).
4. Ito, H., ASME Paper 58-SA-14.
5. Ledinegg, N., Maschinenbau und Waermewirtschaft, 3, No. 4 (1948).

Key words: Boiling heat transfer; carbon; cavitating venturis; cleaning; coatings; flight vehicle tankage; flow oscillations; flow rates; gas generators; heat exchangers; heat transfer coefficient; heat transfer equipment; instability; insulation; liquid oxygen; missiles and rockets; pressure oscillations; pressurization; pressurization failures; pressurization systems; tar; vaporizers.

SIMULATION OF SATURN V S-II STAGE PROPELLANT FEEDLINE DYNAMICS

Ryan, R. S., Kiefling, L. A., and Buchman, H. J. (National Aeronautics and Space Administration, Huntsville, Ala., George C. Marshall Space Flight Center)

J. Spacecr. Rockets 7, No. 12, 1407-12 (Dec 1970)

Oscillations involving the propellant feedlines, engines, and longitudinal structural modes of the Saturn V S-II stage are investigated using an electronic analog computer. The methods used to develop mathematical models and some problems encountered are described. The effect of cavitation at the pump inlet is studied. The simulation was able to match several characteristics of one flight including stability variations with NPSH, amplitude sensitivity, and nonlinear wave forms. The cause of the limit cycle which occurred on two flights was not found. The need exists for accurate and complete test data, especially for structural damping and local and engine dynamics.

This report is concerned with analysis of one variation of the "POGO" effect which has accounted for failures and near failures in the U.S. and European space ventures. The complex coupling between structural vibrations, control reactions, and pump cavitation makes the problem difficult to analyze. This analysis was not very successful in the quantitative results, probably due to an inability to deal with cavitation in the pump. However, useful qualitative conclusions were reached, and these should aid in overcoming the problem.

Important references:

1. Rubin, S., J. Spacecr. Rockets 3, No. 8, 1188-95 (Aug 1966).

2. Sack, L. E. and Nottage, H. B., J. Basic Eng. 87, No. 2, 917-24 (Dec 1965).

3. Stripling, L. B. and Acosta, A. J., J. Basic Eng. 84, No. 3, 339-50 (Sep 1962).

Key words: Analytical model; bubble dynamics; bulkheads; cavitation; cavitation or erosion damage; excessive vibrations; feed lines; fluid oscillations; frequency effects; gas bubble collapse; intermediate bulkheads; liquid oxygen; manned spacecraft; mathematical analysis; mathematical model; NPSH; oxidizer tank; pressurization; pumps; resonances; rocket engines; spacecraft tankage; structural analyses; structural damages; ullage space; vibration analyses; vibrations.

THERMAL-ACOUSTIC OSCILLATIONS INDUCED BY FORCED CONVECTION HEATING OF DENSE HYDROGEN

Thurston, R. S. (New Mexico University, N.M.)

Ph.D. Dissertation, New Mexico Univ. (1966)

Thermal acoustic oscillations occur under conditions of pressure, flow, and high heat flux which produce a dense core of liquid surrounded by a superheated vapor film near the inlet. This phenomenon may even occur above the critical pressure in which case one would refer to a dense core and a less dense annular film.

At high rates of heat transfer, a rapidly growing superheated film could overshoot the thickness conducive to equilibrium between flow rate, heat flux, and fluid properties. If a superheated film is too thick for the heat flux and flow rate, condensation of vapor at the boundary of the film and core may occur. The result would be a decreasing pressure and an acceleration of the interface of the superheated film and core back toward the wall. Repetition of the process would produce oscillations.

Acoustic frequencies of Helmholtz and open pipe resonance were used as references for correlation of the observed frequencies, and the amplitudes of pressure oscillations were related to boiling numbers. In hydrogen experiments with a 1/4 inch by 10 foot long electrically heated tube, maximum peak-to-peak pressure amplitudes of 50 psi were observed. These oscillations should not be confused with the "thermal acoustic" oscillations often encountered in closed tubes leading from liquid helium to a warm environment.

This report is concerned with liquid hydrogen results only. A later paper by Edeskuty and Thurston (1967) compares the similarity relations for oscillation inception with data for liquid nitrogen. This latter result, and that of Platt and Wood (1962) for liquid oxygen, substantially uphold the similarity relations of Thurston.

Important references:

1. Thurston, R. S., Advan. Cryog. Eng. 10, 305 (1965).

2. Thurston, R. S., Rogers, J. D. and Skoglund, V. J., Advan. Cryog. Eng. 12, 438 (1967).

3. Williamson, Jr., K. D. and Bartlit, J. R., Advan. Cryog. Eng. 10, 375 (1965).

Key words: Boiling heat transfer; convection heat transfer; flow instability; flow patterns; forced convection; fluid oscillations; heat exchangers; heat transfer equipment; liquid hydrogen; liquid oxygen; laminar flow; nuclear engine testing; parahydrogen; pressure oscillations; resonance tubes; resonances; storage; subcooled fluids; supercritical fluids; thermal-acoustic oscillations; thermal oscillations; transportation; tubes; turbulent flow; two-phase.

ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF THERMAL AND HELIUM LIFT-PUMPING RECIRCULATION SYSTEMS

Trucks, H. F., and Randolph, W. O. (National Aeronautics and Space Administration, Huntsville, Ala., George C. Marshall Space Flight Center)

Advan. Cryog. Eng. 10, 341-52 (1965)

Geysering is a process by which rapid vapor formation within liquid-filled vertical columns causes rapid expulsion of all or portions of the contained liquid into an overhead container; liquid re-entering the column may then cause detrimental pressure surges due to a water hammer effect. Recirculation of liquid from the supply tank to the bottom of the column can lower the temperature at the bottom of the column and suppress geysering.

Geysering and insufficient pump NPSH were problems in the Saturn V S-IC stage liquid oxygen suction lines. Recirculation by thermal and helium lift-pumping were investigated as possible remedies. A computer analysis was carried out for both modes of recirculation, and the computed results were compared with liquid oxygen experimental results from Marshall Space Flight Center. The computer program accurately predicted the experimental recirculation rates and mean return line temperatures as a function of the heat flux or helium injection rates.

Conclusions were that thermal pumping performance is strongly dependent on heat flux, and helium injection is a reliable means of initiating the recirculation without geysering. Thermal pumping systems are unstable at low hydrostatic heads; however, helium injection in the return line stabilizes the oscillatory flow by accelerating the flow rate and subcooling the recirculating liquid.

Although experimental verification of analytical procedures is limited to liquid oxygen, the analysis should be applicable to other fluids. Generalized solutions would be of benefit if they could be accomplished.

Important references:

1. Griffith, P., ASME Paper No. 62-HT-39 (1962).

2. Morgan, S. K.and Brady, H. F., Advan. Cryog. Eng. 7, 206 (1962).

3. Randolph, W. O. and Vaniman, J. L., MTP-S and M-P-61-19.

4. Clark, J. A., Larsen, P. S., Randolph, W. O. and Vaniman, J. L., Advan. Cryog. Eng. 8, 507 (1963).

Key words: Circulation; computer programs; equations; flow rates; fluid dynamics; fluid oscillations; gaseous helium; gas injection; geysering; instability; lift pumping; liquid oxygen; missiles and rockets; natural convection; pressure surges; propellant conditioning; propellant systems; pumping; pump malfunctions; recirculation; space applications; space vehicles; storage; subcooling; tank failures; thermal pumping; vapor formation; water hammer.

CRITICAL TWO-PHASE FLOW OF NITROGEN AND OXYGEN THROUGH ORIFICES
Bonnet, F. W. (Union Carbide Corporation, Tonawanda, New York, Linde Division)
Advan. Cryog. Eng. 12, 427-37 (1967)

If a saturated liquid is allowed to escape through an orifice from a high pressure into a low pressure reservoir, the flow rate will increase, up to a point, as the receiver pressure is lowered. The maximum flow rate which can be reached by lowering of the receiver pressure is known as the critical or choking flow. In two-phase flow the situation is greatly complicated, compared to superheated gas, by mass, heat, and momentum exchange. Numerous solutions exist, based on a variety of idealized theoretical or semi-empirical models which disagree widely.

Experimental data for cryogenic fluids have been lacking; therefore, experiments with nitrogen were designed to establish whether the homogeneous, thermal equilibrium model or the separated-phase model best fits the data. The best correlation would then be used for oxygen predictions. The homogeneous flow predictions were in reasonably close agreement (10%) with the measured rates. Correlation curves for oxygen and nitrogen are presented.

Considerable differences were found between the solutions of the present author and Smith (1963) for nearly the same models. These were suggested to be due to differences in thermodynamic data; however the differences appear too large to be attributed to that cause alone. The working curves presented by the present author are carried to considerably higher pressures than those of Smith (1963). Smith's range was limited by inconsistancies in available property data.

Important references:

1. Smith, R. V., Nat. Bur. Stand. (U.S.) Tech. Note 179 (Aug 1963).

Key words: Critical (choking) two-phase flow; fluid flow; gaseous; leaks; liquid; mathematical models; nitrogen; orifice flow; orifices; oxygen; pressure drop; two-phase flow.

TWO-PHASE [LIQUID-VAPOR] MASS-LIMITING FLOW WITH HYDROGEN AND NITROGEN
Brennan, J. A., Edmonds, D. K., and Smith, R. V. (National Bureau of Standards, Boulder, Colorado, Cryogenics Division)
Nat. Bur. Stand. (U.S.) Tech. Note 359 (Jan 1968)

Experimental data on critical (choked) flow at the exit of a constant area test section for the two-phase fluids hydrogen and nitrogen are reported. Data are compared to models recommended by Smith in NBS-TN 179 (1963). It was found that the models recommended to provide upper and lower limits of the flow rate did generally bracket the data as intended and that the homogeneous metastable (frozen flow at exit) model predicted the critical flow rate reasonably well, somewhat better for hydrogen than for nitrogen. Oxygen flow data would be expected to be similar to that of nitrogen.

Important references:

1. Moody, F. J., J. Heat Transfer 87 (1965).

2. Smith, R. V., Nat. Bur. Stand. (U.S.) Tech. Note 179 (Aug 1963).

Key words: Analytical model; concentration effects; critical (choking) two-phase flow; critical flow; flow tests; hydrogen; mass-limiting flow; nitrogen; orifice flow; oxygen; quality; storage; transportation; two-phase flow; vaporization.

CRITICAL FLOW RATE OF TWO-PHASE NITROGEN

Campbell, Jr., H. M., and Overcamp, T. J. (National Aeronautics and Space Administration, Huntsville, Ala., George C. Marshall Space Flight Center)

NASA Tech. Memo. X-53492 (Jul 1966)

Data are presented for critical two-phase flow through an orifice. Data are compared with results using analytical models by Levy, Moody and Ward. Best agreement was reported with that from Ward.

Generalized curves for critical pressures and flow rates are presented for hydrogen, nitrogen and oxygen. There appears to be an error in the curves for nitrogen and oxygen using the Moody model. Also there is some controversy as to whether true critical two-phase flow can be developed in orifices.

Important references:

1. Levy, S., J. Heat Transfer 87 (1965).

2. Moody, F. J., J. Heat Transfer 87 (1965).

3. Ward, W. D., Proceedings of the Conference on Long Term Cryopropellant Storage in Space, National Aeronautics and Space Administration, Huntsville, Ala., George C. Marshall Space Flight Center (Oct 12-13, 1966).

Key words: Critical (choking) two-phase flow; critical flow; critical pressure; liquid hydrogen; liquid nitrogen; liquid oxygen; mathematical models; orifice flow; orifices; quality; two-phase; two-phase flow; annular flow.

THE TWO-PHASE CRITICAL FLOW OF ONE-COMPONENT MIXTURES IN NOZZLES, ORIFICES AND SHORT TUBES

Henry, R. E., and Fauske, H. K. (Argonne National Laboratory, Argonne, Ill.)

J. Heat Transfer 93, 179 (May 1971)

An analytical model for two-phase critical flow is presented which uses stagnation fluid properties. This form has an advantage for designers because stagnation properties are generally better known than those at the point of critical flow. Results from the model are compared with data for H_2O, CO_2, air-liquid H_2O and N_2. The model is shown to predict the critical flow rates reasonably well. Similar results with oxygen could be expected because agreement is shown for a number of experimental systems and fluids, including nitrogen, with properties similar to oxygen.

The model is assumed to be limited to cases where the wall frictional forces are negligible compared to momentum-change forces.

Important references:

1. Campbell, H. M. and Overcamp, T. J., NASA Tech. Memo. X-53492 (1966).

2. Bonnet, F. W., Advan. Cryog. Eng. 8 (1966).

3. Henry, R. E., Hendricks, R. C., Simoneau, R. J. and Watterson, R., to be published as a NASA TN.

Key words: Carbon dioxide; compressible flow; critical (choking) two-phase flow; critical flow; flow rates; flow velocities; geometry effects; mass transfer; mathematical model; nitrogen; nozzles; orifice flow; oxygen; potassium; pumps pipings and fittings; quality; saturated liquid; saturated vapor; stagnation; subcooled fluids; two-phase flow; water.

REVIEW OF CRITICAL FLOW RATE, PROPAGATION OF PRESSURE PULSE, AND SONIC VELOCITY IN TWO-PHASE MEDIA

Hsu, Y. Y. (National Aeronautics and Space Administration, Cleveland, Ohio, Lewis Research Center)

NASA Tech. Note D-6814 (Jun 1972)

In this report, the author summarizes the basic concepts of the field — particularly the relationships between single-phase and two-phase critical flow, and between the sonic velocity and critical flow velocity. For the single-phase case, sonic and critical velocities are essentially the same; for the two-phase case, the velocities may differ because the interface process necessary to achieve equilibrium may be slower than the rates of change of pressure in the sonic and critical flow processes.

Analytical models proposed by Fauske, Moody, Levy, and Henry are then reviewed, and those author's comparisons with experimental data are given.

The remainder of the report is devoted to analysis of the propagations of pressure pulses and waves. This represents a combination of developments by the author and reported work in the field.

The report offers minimal design-oriented conclusions or recommendations. General topics discussed are as likely to be applicable to oxygen as to other fluids.

Important references:

1. Henry, R. E., Argonne National Lab. Rept. No. ANL-7430 (Mar 1968).
2. Fauske, H. K., Argonne National Lab. Rept. No. ANL-6633 (Oct 1962).
3. Levy, S., ASME Paper No. 64-HT-8 (1964).
4. Moody, F. J., J. Heat Transfer 87, No. 1, 134-42 (Feb 1965).
5. Henry, R. E. and Fauske, H. K., J. Heat Transfer 93, No. 2, 179-87 (May 1971).
6. Smith, R. V., Advan. Cryog. Eng. 8, 563-73 (1963).

Key words: Acoustic attenuation; critical (choking) two-phase flow; critical flow; liquid hydrogen; liquid oxygen; mathematical models; pressure pulse; pressure pulse duration; saturated liquid; spacecraft tankage; stagnation point; storage; tank draining; tanks; theoretical studies; transportation; two-phase flow; velocity of sound; vessels; water.

CHOKING TWO-PHASE FLOW LITERATURE SUMMARY AND IDEALIZED SOLUTIONS FOR HYDROGEN, NITROGEN, OXYGEN, AND REFRIGERANTS 12 AND 11

Smith, R. V. (National Bureau of Standards, Boulder, Colo., Cryogenics Division)

Nat. Bur. Stand. (U.S.) Tech. Note 179 (Aug 1963)

The literature summary presents a brief description and discussion of papers on choking two-phase flow. These papers are arranged with respect to analysis methods and experimental systems. The idealized solutions utilize models intended to provide upper and lower limits for the actual flow cases. Charts are presented to provide for rapid determination of choking flow for the choking point condition and for Fanno and isentropic flow for the fluids H_2, N_2, O_2, CCl_2F_2, and CCl_3F. A discussion of choking flow and relaxation phenomena is included.

A useful summary of the various models is given in tabular form. With this table and some of the explanatory material, it is often possible to decide which flow process is most applicable to the problem in question. The appropriate equations and solution charts can be located by use of the table. In calculating these charts, the author ran into difficulty with oxygen at pressures above three atmospheres because of the inconsistencies in the enthalpy and specific heat data available at that time. For that reason, the solution charts for oxygen were not carried to as high pressures as desired. Since better data is now available, e.g., McCarty and Weber (1971), these charts could be extended. [Ed. Note: The charts have been extended in an updated version of this report now in preparation by R. V. Smith].

Important references:

1. Smith, R. V., Advan. Cryog. Eng. 8, 563-73 (1963).

Key words: Choking point; critical (choking) two-phase flow; equations; Fanno-flow; flow rates; freon 11; freon 12; gaseous oxygen; hydrogen; isentropic flow; liquid; mass-limiting flow; mathematical models; nitrogen; quality; relaxation phenomena; two-phase; two-phase flow.

B

CRITICAL TWO-PHASE FLOW FOR CRYOGENIC FLUIDS

Smith, R. V. (Cryogenics Division, National Bureau of Standards, Boulder, Colo.)
Randall, K. R., and Epp, R. (Wichita State University, Wichita, Kans.)
Nat. Bur. Stand. (U. S.) Tech. Note (In Press 1972)

This work presents a state-of-the-art survey intended to be useful to a designer of equipment involving two-phase flow of cryogenic fluids. It is desirable to assess the probability of critical, or choking, flow in such a system and, if possible, estimate the critical flow rate.

The literature is surveyed, primarily since Smith (1963), and the predictive results for several analytical models are evaluated and compared with experimental data. These results are discussed; however, no firm conclusions are reached because often the spread of experimental data is equivalent to the predictive results from the models.

Finally, computer evaluations are presented for oxygen, hydrogen and helium along with some design recommendations.

Important references:

1. Carofano, G. C. and McManus, H. N., Progress in Heat and Mass Transfer, Vol. 2 (Pergamon Press).
2. Cruver, J. E. and Moulton, R. W., AIChE, J. 13, 52 (1967).
3. Fauske, H., Proc. 1961 Heat Transfer and Fluid Mechanics Inst., Stanford University Press, Stanford, California, 79 (1961).
4. Henry, R. E., ANL-7740.
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9. Smith, R. V., J. Basic Eng. 94D, No. 1, 147-55 (Mar 1972).

Key words: Critical (choking) two-phase flow; critical flow; geometry effects; interface effects; liquid helium; liquid hydrogen; liquid oxygen; mathematical models; predictive methods; state-of-the-art reviews; two-phase; two-phase flow.

ORBITAL REFUELING TECHNIQUES
Boretz, J. E. (TRW Systems Group, Redondo Beach, California, Electrical Systems Laboratory)
J. Spacecr. Rockets 7, No. 5, 513-22 (May 1970)

This paper is concerned with propellant transfer problems arising from the absence of a strong gravitational field and a well defined liquid-vapor phase distribution in orbiting vessels. Transfer schemes discussed and analyzed include tank replacement, positive displacement bladders or pistons, settling of the liquid by angular or linear acceleration, low NPSH pumps, gas pressurants, surface tension screens, and dielectrophoresis.

Tank replacement appears to be suitable for resupply of life support fluids or small quantities of propellants. Bladders and pistons, though conceptually simple, suffer from practical shortcomings: porosity, leakage, embrittlement at low temperatures — hence short cycle life. Use of bladders has been limited to small quantities of non-cryogenic fluids.

Linear acceleration by means of small engines provides a straightforward solution to transfer problems, but the flow rate achievable is proportional to the acceleration, which is undesirable from a navigational standpoint. As an example, the 10^{-4} g needed to refill a Saturn S-IVB stage in 1.5 hours through a 12 inch line is considered an objectionably high acceleration for that length of time. Gas pressurization or pumping, in combination with acceleration, will have to be employed.

Positioning of the liquid with respect to the vapor and stability of the liquid-vapor interface are functions of the g level. Instability, vortexing, dropout (development of a void above the drain) can result in vapor ingestion or outage of liquid in the receiver vessel (loss through the vapor vent). A criterion is derived for the "settling" of the liquid, i.e., the overcoming of surface tension effects to position the liquid in the drain prior to transfer; this is basically the potential theory criterion for stability of surface waves when a dense fluid is suspended above a less dense fluid. Settling is stated to be assured when the gravity forces are large compared to the surface tension forces. The vapor ingestion and receiver outage problem is also attacked through potential flow theory to determine the shape of the interface during draining and filling. From the shape of the interface above the drain, the vapor ingestion and percent outage can be estimated. The behavior of the draining process is found to be characterized primarily by the Weber number — the ratio of inertia to surface tension forces.

The method of Gluck and Kline (1962) for estimating gas pressurant mass requirement is outlined as well as the transfer line cooldown transient analysis of A. D. Little (1959). Receiver tank cooldown and generation of vapor are also considered. Cooldown time for the tank, and quantity of vapor formed, are obtainable from solutions of the usual conservation equations, provided the necessary heat transfer coefficients can be predicted.

Dynamic instability due to the motion of fluids during transfer could result in tumbling or other unstable conditions. Linear and angular momentum equations may be solved by use of a potential function for the draining flow obtained from a study by Bhuta and Koval (1965).

One method used to prevent the loss of liquid during venting involves the use of a throttle valve and heat exchanger in the vent. Evaporation of liquid as it is vented provides refrigeration.

Dielectrophoresis is a relatively new method of orienting fluids by use of electric polarizing forces. This is accomplished through the use of parallel screen electrodes on either side of the drain to shape the interface above the drain port in such a way as to minimize "pull through" of vapor. Uncharged screens can also be used to prevent vapor from entering the liquid drain port; screens of proper mesh size allow

(Continued)

liquid to pass through but present a barrier to vapor bubbles because of surface tension effects at the interface.

Pumps of low net positive suction head are of great advantage in orbital transfer. An improved criterion for prediction of cavitation is described (Boretz 1961).

Finally, the use of figures of merit for selection of an optimum refueling concept is discussed. Factors which must be considered are total payload fraction, cost effectiveness, and reliability. More intangible are considerations such as safety, maintainability, availability, and development risk.

This paper covers a broad range of orbital fluid transfer problems and would appear to be a good introduction to that subject. One transfer scheme, the use of angular acceleration, listed at the beginning was not covered in the text.

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1. Coxe, E. F. and Tatom, J. W., Advan. Cryog. Eng. 7, 234-43 (1962).
2. Nein, M. E. and Thompson, J. F., NASA Tech. Note D-3177 (Feb 1966).
3. Gluck, D. F. and Kline, J. F., Advan. Cryog. Eng. 7, 219-33 (1962).
4. Special Report No. 106, Pressurized Cooldown of Cryogenic Transfer Lines, A. D. Little, Oct. 1, 1959.
5. Martinnelli, R. C. and Nelson, D. B., Trans. ASME 70, 695 (1948).
6. Bhuta, P. G. and Koval, L. R., Proceedings of the Symposium on Fluid Mechanics and Heat Transfer Under Low Gravity, Palo Alto, Calif., June 24, 1965.
7. Blackmon, J. B., J. Spacecr. Rockets 2, No. 3, 391-8 (May-Jun 1965).
8. Evans, E. A. and Walburn, A. B., J. Spacecr. Rockets 6, No. 10, 1189-93 (Oct 1969).
9. Burge, G. W., Blackmon, J. B. and Madsen, R. A., AIAA Paper 69-567, U.S. Air Force Academy, Colo. (1969).
10. Morgan, L. L., AIAA Paper 69-565, U.S. Air Force Academy, Colo. (1969).

Key words: Acceleration effects; cavitation; cooldown; dielectrophoretic liquid expulsion; expulsion bladder; flow instability; fluid oscillations; fuels; gravity effects; gravity transfer; hazards; interfacial phenomena; interface; instability; liquid-vapor interface; liquid hydrogen; liquid oxygen; mass transfer; materials embrittlement; NPSH; orbital liquid transfer systems; orbital tankers; pressurization gas requirements; pressurized transfer pumps; propellants; selection criteria; spacecraft; spacecraft tankage; surface tension devices; tank draining; venting; vortex formation; zero gravity.

ANALYSIS OF TWO-PHASE IMPINGEMENT FROM A CRYOGEN VENTED IN ORBIT
Evans, E. A., and Walburn, A. B. (General Dynamics, San Diego, Calif., Convair Division)
J. Spacecr. Rockets 6, No. 10, 1189-93 (Oct 1969)

The impingement forces on surfaces in the vicinity of liquid hydrogen or liquid oxygen being vented into vacuum were investigated. Under the assumption of steady flow the problem was considered as spacially dependent flow of a two-phase mixture with interphase mass transport and drag forces. Choked flow conditions were assumed at the discharge orifice. By means of Newtonian impact theory, modified by momentum exchange considerations at the impingement surface, the impingement force was obtained from the momentum flux.

The method of characteristics solution for the gas flow field was carried out by means of an analog computer.

An important result of the computations is that the forces due to re-emission of material from the impingement surface are of the same order of magnitude as the impact forces. This analysis appears to offer a considerable advancement in the theory of expansion of cryogens into vacuum.

Important references:

1. Walburn, A. B., American Astronautical Society Southeastern Symposium in Missiles and Aerospace Vehicles Sciences (Dec 1966).

Key words: Gas expansion; impingement; liquid hydrogen; liquid oxygen; missiles and rockets; sorption; spacecraft; spacecraft tankage; space venting; storage; surface effects; theoretical studies; transportation; two-phase flow; vacuum; venting.

FLUID DYNAMICS: IV. GEOMETRY EFFECTS, Chapter 5
Smith, R. V. (National Bureau of Standards, Boulder, Colo., Cryogenics Division)
Haseldon, G. G. (ed.), Cryogenic Fundamentals, Academic Press, 250-77 (1971)

Section IV of this chapter deals with flow through valves, orifices, curves, fittings, packed beds, etc. The distinguishing feature of these flows is that additional pressure losses are caused by turbulent separation and secondary flows which are not present in straight pipes. Equivalent lengths of straight pipes for various valves and fittings are tabulated as well as flow coefficients for orifices and venturis.

The results of Brennan (1964), Purcell et al. (1960) and Richards et al. (1959) are cited. These studies showed that orifices and venturis may be used successfully as flow meters for liquid hydrogen and nitrogen even though the minimum pressures fall below the saturation pressure. In view of the similarities between nitrogen and oxygen properties, it is reasonable to extend these conclusions to oxygen flow measurement. However, since the limitations on permissible pressure reduction below saturation are not well known, these meters should be used with due caution. Flow coefficients established with subcooled liquids could also lead to incorrect pressure drop calculations where the liquid is saturated.

Additional topics covered are flow through curved tubes, entrance effects, noncircular conduits, tube banks, annuli, and compressible flow through restrictions.

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1. Ito, H., J. Basic Eng. 81, 123-34 (1959).
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5. Kays, W. M. and London, A. L., Compact Heat Exchangers, McGraw-Hill Book Co., New York (1958).
6. Fluid Meters, Their Theory and Application, 5th ed, ASME Publication (1959).
7. Richards, R. J., Jacobs, R. B. and Pestalozzi, W. J., Advan. Cryog. Eng. 4, 272-85 (1959).
8. Close, D. L., Cryog. and Ind. Gases 4, 19, 21-3 (Aug 1969).

Key words: Fittings; flow meters; geometry effects; laminar flow; liquid hydrogen; liquid nitrogen; liquid oxygen; nozzles; orifices; pipes; pressure drop; Reynolds number; size effects; turbulent flow; valves; valves and controls; venturi.

CAVITATION STATE OF KNOWLEDGE
Robertson, J. M., and Wislicenus, G. F., eds. (Illinois Univ.)
ASME Publication, New York (1969)

The purpose of this symposium is well stated by J. Robertson. "At the current rate of appearance of cavitation papers - some sixty per year - one would keep rather busy just studying them all. This type of cavitational problem is one which this symposium hopes to ameliorate somewhat by providing an up to date summary of where we are." The individual articles include such topics as liquid tensile strengths, cavitation in turbulent boundary layers, limited cavitation, collapsing bubble damage to solids, cavitation effects in pumps and turbomachinery. Data or results of cavitation in liquid oxygen are not specifically presented in this symposium; however, most of the results discussed can apply to any liquid. Some comments made by the various authors on the state of the knowledge of cavitation which could have direct bearing on cavitation in liquid oxygen are summarized as follows:

1) More work is needed for the understanding of the scale effects of cavitation in going from smaller model studies to the full size prototype.

2) The thermodynamic effect of various liquids is still considered to be only a partially solved problem.

3) Several complications preclude the quantitative prediction of cavitation damage resistance of a new material in terms of easily measurable mechanical properties.

4) Wall effects (theoretically determined) in cavity flows are found to be more important for thin or slender bodies than for blunt ones.

5) None of the published work on cavitation research has progressed to the point where quantitative predictions of the cavitation effects in pump design are firmly established.

6) Cavitation has been used as the basis of control devices in which the flow rate depends only on the upstream pressure since the downstream pressure is fixed by cavitation. Thus, in a rocket propulsion system, the flow of liquid propellant was made independent of downstream occurrences through the use of cavitating valves.

The above list is certainly not inclusive, but it does show that the phenomenon of cavitation is not well understood, that its effects are difficult to predict, and that in some cases cavitation is beneficial.

Key words: Boundary effects; cavitation; cavitation erosion or damage; erosion; flow control valves; geometry effects; inducers; liquid oxygen; missiles and rockets; nucleation; predictive methods; propellant transfer systems; pump cavitation; pump design; pumps; scaling relationships; symposia turbopumps; valves.

FIRE TESTS ON CENTRIFUGAL PUMPS FOR LIQUID OXYGEN

Bauer, H., Wegener, W., and Windgassen, K. F. (Cryostar AG, Basel, Switz.)
Cryogenics 10, No. 3, 241-8 (Jun 1970)

In order to clarify the conditions under which fires or explosions may occur in centrifugal pumps for liquid oxygen, tests were conducted with pumps made of aluminum, bronze, and stainless steel alloys. All tests were started only after adequate preliminary cooling of the pump had been carried out and after the pump was full of liquid. Incipient and fully developed cavitation was induced in the pump during these tests. It was found that pumps with bronze casings and impellers provide the greatest security against fire and explosion damage. Although no fires or explosions are attributed directly to cavitation, it is recommended by the authors that cavitation inside the pump be avoided. Cavitation damage or pump performance during these above tests are not reported.

Key words: Abrasion particles; aluminum alloy; brass; bronze; carbon; cavitation; centrifugal pumps; chrome-nickel steel; compatibility; copper; explosion characteristics; explosions; fires; friction; gaseous oxygen; ice; ignition temperature; ignition tests; impact loads; liquid oxygen; materials compatibility; materials failure; materials selection; metallic abrasion; metal rub; nickel; particulate contamination; pumps; rotating parts; rust; solder; stainless steel; strainers; temperature rise; temperature sensors; testing procedures; titanium.

THERMODYNAMIC DEPRESSIONS WITHIN CAVITIES AND CAVITATION INCEPTION IN LIQUID HYDROGEN AND LIQUID NITROGEN

Hord, J., Edmonds, D. K., and Millhiser, D. R. (National Bureau of Standards, Boulder, Colo., Cryogenics Division)

National Aeronautics and Space Administration, Cleveland, Ohio, Report No. CR-72286 (Mar 1968)

Cavitation characteristics of liquid hydrogen and liquid nitrogen in a transparent plastic venturi have been determined. The data reported in this work were instrumental in the determination of the exponents used in the B-factor equation of the RMG pump cavitation prediction method. The detection techniques reported here should, with the proper precautions, also apply to liquid oxygen. An acoustic transducer and the signal conditioning instruments for the detection of cavitation inception are described. Cavitation was readily discernible on the oscilloscope and was characterized by large-amplitude, high-frequency signals. Acoustical techniques have recently been used in analyses of cavitation in turbo-machinery.

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Key words: Acoustic detection; B-factors; cavitation; cavitation detection; cavitation inception; flow rates; instrumentation; liquid hydrogen; liquid nitrogen; liquid oxygen; prediction methods; venturi.

NUCLEATION CHARACTERISTICS OF STATIC LIQUID NITROGEN AND LIQUID HYDROGEN

Hord, J., Jacobs, R. B., Robinson, C. C., and Sparks, L. L. (National Bureau of Standards, Boulder, Colo., Cryogenics Division)

J. Eng. Power 86, 485-94 (1964)

This paper is not concerned with the precise nature of the nuclei (cosmic rays, vortices, stabilized microbubbles, etc.) but rather, deals with the thermodynamic characteristics which control the existence of metastable (superheated) liquid states and the nucleation of the vapor phase. The test liquid, initially in thermodynamic equilibrium, was superheated by reducing the ullage pressure in the vessel. Experimental superheat limit curves for liquid nitrogen and liquid hydrogen, statically contained in a nearly ideal (acid cleaned, smooth glass) system, are presented and compared with theoretical limit curves. Results of these experiments are summarized as follows:

1. Liquid nitrogen, statically contained in an acid-cleaned glass system, can be maintained in highly metastable states for several seconds (persistence times).

2. Liquid hydrogen, statically contained in an acid-cleaned glass system, can be maintained in highly metastable states for tens of milliseconds.

3. The presence of stainless steel, brass, or aluminum surfaces with finishes from 4 to 78 microinches does not appreciably affect the amount of superheat that can be attained by liquid nitrogen in the apparatus, relative to clean glass surfaces, but appreciably shortens persistence times.

4. The presence of stainless steel, brass, or aluminum surfaces with finishes from 4 to 78 microinches does not appreciably affect the amount of superheat attainable with liquid hydrogen in the apparatus, or the persistence times, relative to the clean glass system. The presence of a very rough (200 + microinches) stainless steel surface in liquid hydrogen does appreciably affect the amount of superheat attainable, as well as nucleation time.

5. The presence of solid contaminants (nitrogen, carbon dioxide, and water) significantly decreases both the superheat attainable and the nucleation times for liquid nitrogen and liquid hydrogen relative to a clean glass system.

6. The theory developed here for predicting the nucleation pressures for isolated liquids agrees with experimental results for those cases where apparatus limitations do not prevent a comparison. In order to evaluate the theory for liquid nitrogen and liquid hydrogen down to the normal boiling points, an apparatus that can apply tension to the liquid will be required.

The experimental data also indicate that nucleation information obtained from boiling studies is not applicable to nucleation achieved by pressure reduction. In all of these experiments nucleation was found to originate on a liquid-solid interface. The theory developed in the text is in fair agreement with the experimental data for the nearly ideal system. This theory is not restricted to nitrogen or hydrogen and should apply to liquid oxygen as well. To apply this theory to hydraulic machinery one needs to know the minimum pressure values in a particular machine for a given flow situation. Persistence of the metastable state is shown to be dependent upon the rate of pressure decay, the initial equilibrium pressure, fluid environment, and the nucleation pressure.

NUCLEATION CHARACTERISTICS OF STATIC LIQUID NITROGEN AND LIQUID HYDROGEN

Hord, J., Jacobs, R. B., Robinson, C. C., and Sparks, L. L.

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Key words: Aluminum; brass; bubble formation; carbon dioxide; cavitation; cavitation erosion or damage; contaminants; contamination; fluid transfer; glass; liquid hydrogen; liquid nitrogen; liquid oxygen; metastable state; nucleation; particulates; pumps; pumps pipings and fittings; solidified gas; stainless steel; surface finish; surface preparation; superheated fluid; theoretical analyses; water.

TURBULENCE DEPENDENCE OF VAPOROUS CAVITATION IN OXYGEN JET

Nishigaki, K., Kato, E., and Saji, Y. (Kobe University of Mercantile Marine, Higashinada-ku, Kobe)

Jap. J. Appl. Phys. 8, No. 12, 1540-5 (Dec 1969)

For the purpose of clarifying the cavitation characteristics and the effect of turbulence on the inception of hydraulic cavitation, liquid oxygen and an oxygen-argon solution were cavitated in a liquid-liquid jet in the temperature range from 70 K to the normal boiling point under various hydrostatic pressures. A controlled differential pressure caused the liquid to flow through a nozzle submerged in the same liquid. At a certain "critical" value of the flow velocity, clouds of visible size bubbles appeared near the jet boundary (away from any solid surface). The first author reported in an earlier paper that choking of the nozzle was coincident with this incipient point, which is similar to the Mach one condition in the flow of compressible fluids. The critical velocity for liquid oxygen was found to be about 24.8 m/s. It was also found that the critical velocity decreased with increasing temperature and could be described satisfactorily by a modified form of Bernoulli's equation. This relationship should also be valid for hydraulic cavitation in other geometries. However, since the value of the critical velocity may depend on the local surface texture, and thermodynamic properties of the fluid, its use as a tool for predicting incipient cavitation in untested situations appears to be limited. Although these data give additional support to the vortex-turbulence theories of nucleation, the exact mechanisms of creating clouds of bubbles from turbulence remains rather obscure.

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Key words: Boundary layers; bubble formation; cavitation; cavitation erosion or damage; cavitation inception; critical (choking) two-phase flow; critical flow; critical velocity; diffusion coefficient; flow rates; heat of vaporization; helium; jets; liquid argon; liquid oxygen; metastable state; nozzles; nucleation; oxygen jet behavior; pumps pipings and fittings; saturated liquid; superheated fluid; turbulence; turbulent flow; vapor pressure; vortex.

THE DYNAMIC BEHAVIOR OF LIQUIDS IN MOVING CONTAINERS
Abramson, H. N., ed. (South West Research Institute, San Antonio, Texas)
National Aeronautics and Space Administration Special Publication No. SP-106 (1966)

A vibrating container or a container subjected to sudden forces can induce cavitation within the contained liquid. The effects of this "dynamically induced" cavitation on the propellant tank structure and the resulting vehicle performance have been of concern in rocket design. The dynamic response of liquids contained in a tank which is vibrated vertically is discussed in Chapter 8 of this document. Experiments using water vividly show what could happen in a vibrating rocket propellant tank. However, at the date of publication these occurrences had not been manifested in actual flights.

The simulation problem of cavitation in a moving tank is discussed in Chapters 5 and 10. An analysis shows that when the prototype liquid is a cryogen, the model must be bigger than the prototype for the range of acceleration scale ratios important to simulation of rocket booster tanks.

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Key words: Bubble dynamics; cavitation; flight vehicle tankage; liquid hydrogen; liquid oxygen; materials failure; missiles and rockets; propellant tanks; rocket performance; simulations; spacecraft tankage; storage; storage tanks; tank damages; vertical; vessels; vibration; water.

DEVICE FOR CAVITATION TESTING OF MATERIALS IN LIQUID OXYGEN
Bolshutkin, D. N., and Krot, Yu. E.
Translated from: Zavod. Lab. 34, No. 11, 1381-2 (Nov 1968)

The effect of ultrsonically induced cavitation on metal surfaces of small area is reported. The tests were conducted in liquid oxygen at a temperature much lower than the boiling point and in room temperature water. The results are compared for a typical copper specimen after a two hour test. The erosion zone with water is larger and more uniform than that of oxygen. Practically no surface oxidation is observed during the tests in oxygen, probably due to the low chemical activity of the cooled material. The author mentions that surface roughness of the specimen is an important parameter in these tests. This paper describes the experimental equipment but the experimental results are not given in depth. Different mechanisms of cavitation damage may be involved in ultrasonically induced cavitation in comparison with cavitation damage in a flow system. Thus a straight extrapolation of results obtained in one system to the other might be very uncertain. Data on material damage due to cavitation in liquid oxygen are scarce; this is the only liquid oxygen cavitation damage work found by the reviewer in the open literature.

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Key words: Cavitation; cavitation erosion or damage; copper; effects of surface texture; erosion; liquid oxygen; materials failure; oxidations; reactivity; storage; subcooled propellants; surface effects; transportation; ultrasonic cavitation; ultrasonic testing; water.

MECHANICS OF CAVITATION ATTACK ON MATERIALS, Chapter 8; and EVALUATING RESISTANCE OF MATERIALS TO CAVITATION DAMAGE, Chapter 9
Knapp, R. T., Daily, J. W., and Hammitt, F. G.
Cavitation, McGraw-Hill Co., New York, 321-61 (1970)

It is known that cavitation can damage almost any adjacent solid surface. Chapter 8 of this book discusses the factors inherent in the cavitation process itself which may produce this damage. In the past, many divergent views concerning the factors in the cavitation process, which are responsible for damage to materials, have been expressed. However, one of the major factors that causes cavitation damage is the purely mechanical one of reoccurring, high-intensity pressures or blows; this factor is always present with cavitation. Experiments have demonstrated that the damage occurs in the collapse phase of the life of a cavity. In flow systems the problem is made difficult because the cavities usually do not form and collapse in the same spot. Zones of cavitation damage are sometimes found, for example, in the discharge portion or even in the diffuser of some centrifugal pumps. This zonal damage is probably caused by the ability of traveling cavities to rebound several times before finally collapsing. Experiments aimed at investigating the damage characteristics, the relation between cavity size and overall rate of damaging blows, the time dependence of the pitting rate, and the size distribution of the damage pits, are discussed. The experiments have shown that at least three kinds of attack are possible: 1) mechanical attack characterized by high intensity infrequent blows due to the impingement either of shock waves propagated in the liquid or of liquid microjets; 2) chemical attack (which is accelerated by high temperatures and pressures); 3) development of electrical potentials which may accelerate chemical attack. The above mechanisms are applicable to cavitation in liquid oxygen. However, because of the low temperatures of liquid oxygen, the chemical effects, item 2), are probably secondary.

Another facet of the problem of cavitation damage is the practical problem of quantitatively determining the resistance that materials display when subjected to cavitation attack; this is discussed in Chapter 9. In the selection of materials for use in liquid oxygen, the designer is restricted to those which are oxygen compatible and those which minimize the potential of inducing fires or explosions (all metallic materials used in engineering are combustible in oxygen). At the present time it is not possible to predict the cavitation resistance of a given material with reasonable accuracy solely from a consideration of its properties and an evaluation of the type and intensity of cavitation to which it will be subjected by the fluid flow regime. All metals subjected to cavitation seem to increase in surface hardness. In the absence of significant corrosion, the best mechanical-property correlation is between cavitation resistance and ultimate resilience. Experiments also show an increase in cavitation resistance as grain size is reduced. Laboratory methods and experimental results are summarized in Chapter 9. One method of particular interest is a rotating disk device which generates cavitating flow patterns similar to those often encountered in turbo-machines. Cavitation damage data in liquid oxygen is very scarce and is necessary if the damage due to long term pumping or flow with cavitation present is to be estimated.

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Key words: Acoustic method; aluminum; bubble collapse; bubble dynamics; cavitation; cavitation erosion or damage; cavitation tests; chemical reactivity; compatibility; corrosion; disk; electric fields; erosion; liquid oxygen; magnetostriction; mechanical impact; oxygen pumps; pumps; pump simulation; shock waves; test equipment; venturi; vibration; water.

SOME CHARACTERISTICS OF THE CAVITATION EROSION OF METALS IN LIQUID OXYGEN

Krot, Yu. Ye., Bol'shutkin, D. N., and Gavranek, V. V. (Physical-Technical Institute of Low Temperatures, AN Ukranian SSR, Kharkov)

NASA Tech. Translation No. F-14,164; translated from Fis.-Khim. Mekh. Mat. 5, No. 2, 214-7 (1969)

The effects of ultrasonically induced cavitation on lead, copper, nickel, iron, and zinc specimens immersed in test liquids (liquid oxygen, and water at 20 °C) are reported. The sample materials were polished and placed about 1 mm away from the tip of the ultrasonic driver. In liquid oxygen, iron and zinc were found to have high damage resistance (higher than in water). Damage resistance was determined from sample weight loss. None of the metals investigated were oxidized in cavitating oxygen, probably because of the low temperatures involved.

The following conclusions were made by the authors:

1. Materials which remain plastic when cooled to -196 °C are less resistant to the cavitation effect of oxygen (over a period of four hours at a vibration amplitude of 15 μ) than brittle materials.

2. Degassing liquid oxygen causes the microshock effect of oxygen to exceed that of water.

3. There is no corrosion of materials in the cavitation action of oxygen, making it possible to study more extensively the role of the mechanical factor of cavitation.

A firm correspondence between ultrasonically induced cavitation and cavitation in hydraulic systems has not been established (different mechanisms may be involved). Therefore, extrapolation of the present results to hydrodynamic cases should be done with reservation. More liquid oxygen cavitation damage data are needed on materials most commonly used in liquid oxygen flow systems.

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Key words: Cavitation; cavitation erosion or damage; copper; degassing; erosion; erosion rates; iron; lead; liquid oxygen; microshocks; nickel; oxidation; ultrasonic vibrations; water; weight losses; zinc.

DETERMINATION OF NPSH ON LARGE CENTRIFUGAL PUMPS AND THOMA'S LAW OF SIMILARITY

Fang, K. S., and Koolhof, F. (FMC Corp., Los Angeles, Peerless Pump Div.)
1971 Cavitation Forum, Proc. 1971 Fluids Engineering Conf., May 10-12, 1971, Pittsburgh, Penn. American Society of Mechanical Engineers, New York, N.Y.

Cavitation performance of geometrically similar pumps at a one percent head or efficiency dropoff (whichever occurred first) are compared. The authors find that the Thoma number — NPSH/H, where H is the developed head — tends to increase with increasing size of the pump. The present data are not sufficient to generalize this apparent size effect and the difference in size alone may not be responsible for all the discrepancies. Although the data show that water rather than liquid oxygen was used here, care must be taken in extrapolating cavitation performance of a smaller size, model pump to the prototype. More pump cavitation scaling data are needed. (Recall that scaling data include other parametric effects in addition to size.)

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Key words: Cavitation; centrifugal pumps; efficiency; head dropoff; liquid oxygen; NPSH; oxygen pumps; pump cavitation; pumps; scaling relationships; size effects; water.

SCALE EFFECTS ON CAVITATION
Holl, J. W., and Wislicenus, G. F. (Nebraska Univ., Lincoln, Nebr.)
J. Basic Eng. 83, 385-98 (1961)

The classical theory of similarity of cavitation expressed by $2(P-P_v)/\rho V^2$ = Constant [where P is the static pressure in a uniform flow upstream of the cavitating object, P_v is the vapor pressure, and V the average upstream flow velocity] states that the cavitation conditions (the form and extent of cavitation voids) in two similar machines or structures with similar flows will be similar. The intent of this paper is to focus attention on the knowns and unknowns of the departures from this classical similarity law of cavitation, i.e., scale effects. A review of the similarity conditions, some experimental data with cold water with submerged flow models (which shed light on the scale effects), and attempts to correlate the above information are presented. In the discussion of scale effects the authors choose to distinguish between effects external to the boundaries of the cavitation voids and effects on the cavitation process itself. The effects of Reynolds number, Froude number, and Mach number are classified as the former, and the effects of the ratio of the vapor pressure to free stream pressure, the ratio of the cavity pressure depression below vapor pressure to free stream pressure, and Weber number, as the latter. The data used in the correlations in this paper are of the desinent point which is a very limited form of cavitation. A significant point in the discussion of this paper is that the conditions in the liquid environment would probably be altered rather significantly once cavitation has occurred. Hence a more realistic approach would be to determine scale effects with developed cavitation.

This paper was written before much of the cavitation data using liquid hydrogen, liquid nitrogen, and other liquids which have relatively strong thermodynamic effects were published. A result of this latter work has been a more general cavitation parameter based on the minimum static pressure (P_c) of the cavity; i.e., $2(P-P_c)/\rho V^2$ = Constant, where $P_c \leq P_v$. The authors conclude that the process of cavitation and its scale effects are not properly understood and that further, careful experimentation and analyses are needed. The same statement could be made today, approximately 11 years later. In the discussion of this paper, it is also emphasized that similarity arguments not based on physical observations are likely to be inappropriate and experiments which delineate the type of cavitation flows are necessary before meaningful similarity arguments can be made.

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Key words: Boundary effects; bubble dynamics; cavitation; cavitation numbers; density; desinent point; Froude number; liquid hydrogen; liquid nitrogen; liquid oxygen; Mach number; Reynolds number; scaling relationships; similarity criteria; vapor pressure; water; Weber number.

COMPARISON AND CORRELATION OF CENTRIFUGAL PUMP CAVITATION TEST RESULTS HANDLING LIQUID OXYGEN AND WATER

Carter, Jr., T. A., Crusan, C. R., and Thodal, F. (Turbocraft Co., Pasadena, Calif.)
Advan. Cryog. Eng. 4, 255-63 (1958)

Results of two pumps tested in water near room temperature, and in liquid oxygen, are reported. One pump is a two-stage, medium pressure, liquid oxygen transfer pump designed for 35 gpm and a 600 ft. head rise at 8400 rpm. An inducer (designed for a suction specific speed of 25,000) is employed in front of the first stage impeller. The second pump is a single-stage transfer pump. Its operating point is 150 gpm with a 125 ft. head rise at 3500 rpm. The cavitation performance with liquid oxygen was found to be better than that obtained with water. With the water data, a predictive technique using calculated B-factors is used by the authors to estimate the liquid oxygen NPSH at the fully cavitating point. The predicted results are only approximate and are not reported for other points along the cavitation curves.

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See also:

1. Ruggeri, R. S. and Moore, R. D., NASA Tech. Note D-5295 (1969).

Key words: B-factors; cavitation; cavitation curves; cavitation performance; centrifugal pumps; equations; fluid dynamics; inducer; liquid oxygen; NPSH; oxygen pumps; pump cavitation; pumps; pumps pipings and fittings; single-stage; two-stage; vapor pressure; water.

JET PUMP CAVITATION

Cunningham, R. G., Hansen, A. G., and Na, T. Y. (Pennsylvania State Univ., University Park, Pa., Dept. of Mechanical Engineering)

ASME Winter Annual Meeting, Los Angeles, Calif., Nov. 16-20, 1969, Paper No. 69-WA/FE-29

Mixing-throat cavitation in a liquid jet pump results from high jet velocities, low suction (NPSH) pressure, or low discharge pressure. Incipient cavitation at the jet boundary has no effect on jet pump efficiency, but under severe conditions it spreads to the walls. A limiting flow condition results which is independent of discharge pressure. Efficiency deteriorates rapidly and the pump head-flow characteristics can no longer be predicted by conventional theory.

Eight correlation parameters (1937-1968) and their interrelations are examined. A Cavitation Index σ_L is recommended for correlation of cavitation-limited flow results. Limiting flow data from 14 references on water, oils, and mercury, plus additional data on three water jet pumps are compared, showing that 11 sets of data on water, oils, and mercury can be represented by the single-number index σ_L, with a range of 0.8 to 1.67. Conventional jet pumps are described by σ_L = 1.0 to 1.4 and σ_L = 1.35 is recommended for conservative use. The limiting flow function Y (NPSH) is shown to be a useful tool in comparing cavitation response to design changes.

System design to avoid cavitation is facilitated by a simple limiting flow equation, $M_L(R, \sigma_L, \text{NPSH}, V_n)$, and the equation is compared with recently published data. Cavitation can be avoided by reducing V_n, and R, or by raising suction port pressure. Flow passage contours, including nozzle-to-throat spacing, influence σ_L and the limiting flow ratio can also be improved by reducing σ_L (0.9 or less) through careful design. Systems handling high gas-solubility liquids can be improved by reducing gas content; fluid properties otherwise have little effect on this jet pump phenomenon.

The information in this paper might have direct application to the recently proposed rocket-powered ejectors for pumping liquid oxygen and liquid hydrogen.

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Key words: Cavitation; cavitation index; efficiency; ejectors; equations; flow patterns; geometry effects; incipient cavitation; jet pumps; jet velocities; limiting flow; liquid hydrogen; liquid oxygen; mercury; missiles and rockets; NPSH; oil; oxygen pumps; pump cavitation; pumps; rocket exhaust; water.

DETERMINATION OF NPSH ON LARGE CENTRIFUGAL PUMPS AND THOMA'S LAW OF SIMILARITY

Fang, K. S., and Koolhof, F. (FMC Corp., Los Angeles, Peerless Pump Div.)
1971 Cavitation Forum, Proc. 1971 Fluids Engineering Conf., May 10-12, 1971, Pittsburgh, Penn. American Society of Mechanical Engineers, New York, N.Y.

Cavitation performance of geometrically similar pumps at a one percent head or efficiency dropoff (whichever occurred first) are compared. The authors find that the Thoma number — NPSH/H, where H is the developed head — tends to increase with increasing size of the pump. The present data are not sufficient to generalize this apparent size effect and the difference in size alone may not be responsible for all the discrepancies. Although the data show that water rather than liquid oxygen was used here, care must be taken in extrapolating cavitation performance of a smaller size, model pump to the prototype. More pump cavitation scaling data are needed.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 126.)

ON THE MECHANISM OF HEAD BREAKDOWN IN CAVITATING INDUCERS
Jakobsen, J. K. (Rocketdyne, Canoga Park, Calif.)
J. Basic Eng. 86, 291-305 (1964)

The mechanism of head breakdown in cavitating inducers, as affected by thermodynamic properties of the pump fluid and scale effects, is discussed. Results of some early cavitation tests on three different pumps, performed with water, liquid oxygen, and nitrogen are reported. These data are for a one percent head dropoff. The test results show a significant increase in suction performance when liquid oxygen (and liquid nitrogen) is used rather than water as the pump fluid. More recent liquid oxygen cavitation data with two similar pumps and two flow rates (the design flow rate and the design flow rate plus 17 percent) are reported for a two percent head dropoff. The data of Carter, Jr. and Crusan and the above are the only liquid oxygen pump cavitation data found (by the reviewer) in the open literature. The values of NPSH for the above conditions are correlated with a critical vapor fraction, derived from a local, unity Mach number condition. The correlation gives support to the author's proposed mechanism of head breakdown but is developed from data obtained from a relatively narrow range of flow coefficients, a single pump geometry, a single value of the percent head dropoff, and a single pump rotative speed. Another difficulty in the use of this theory is the uniqueness of the expression for the two-phase acoustic velocity; i.e., several other expressions are available which would give substantially different values of the two-phase acoustic velocity for the same conditions.

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Key words: B-factors; bubble dynamics; cavitation; cavitation numbers; critical vapor fraction; head breakdown; head dropoff; inducers; liquid nitrogen; liquid oxygen; Mach number; mathematical models; NPSH; oxygen pumps; pump cavitation; pumps; scaling relationships; suction specific speed; thermal parameter; two-phase flow; vapor pressure; velocity of sound; water.

TESTING PUMPS IN AIR

King, J. A. (Rocketdyne, Canoga Park, Calif.)

J. Eng. Power 90, No. 2, 97-105 (1968)

Rocket pumps, designed for operation with liquid oxygen and hydrogen have been tested with air. A good correlation of non-cavitating pump performance was found between the air and cryogenic liquids. Thus, the air data could be used to predict the pump performance in liquid oxygen (and hydrogen or other fluids). In the preinduced pumps tested in air, the static pressure at the inducer exit was found to be a useful indication as to whether the pump cavitates. As pointed out in the discussion in this paper, this testing technique is not new and its application requires some initial testing to verify an accurate correlation of the liquid and air data. Reynolds number effects can also be a problem and need to be considered in the testing analysis. The cavitation incipient point of some turbines has been previously predicted from blade pressure measurements in air. Prediction of developed cavitation performance with air tests is believed to be invalid. Although there are some shortcomings, testing liquid oxygen pumps in air is less expensive, safer, serves as an excellent tool for comparing changes in pump design, and can give some insight into the cavitation performance.

Key words: Axial-flow pumps; cavitation; centrifugal pumps; gaseous air; incipient cavitation; inducers; liquid hydrogen; liquid oxygen; missiles and rockets; oxygen pumps; performance tests; prediction methods; pump cavitation; pumps; Reynolds number; rockets; similarity criteria; turbopumps.

TURBULENCE DEPENDENCE OF VAPOROUS CAVITATION IN OXYGEN JET

Nishigaki, K., Kato, E., and Saji, Y. (Kobe University of Mercantile Marine, Higashinada-ku, Kobe)

Jap. J. Appl. Phys. 8, No. 12, 1540-5 (Dec 1969)

For the purpose of clarifying the cavitation characteristics and the effect of turbulence on the inception of hydraulic cavitation, liquid oxygen and an oxygen-argon solution were cavitated in a liquid-liquid jet in the temperature range from 70 K to the normal boiling point under various hydrostatic pressures. A controlled differential pressure caused the liquid to flow through a nozzle submerged in the same liquid. At a certain "critical" value of the flow velocity, clouds of visible size bubbles appeared near the jet boundary (away from any solid surface). The first author reported in an earlier paper that choking of the nozzle was coincident with this incipient point, which is similar to the Mach one condition in the flow of compressible fluids. The critical velocity for liquid oxygen was found to be about 24.8 m/s. It was also found that the critical velocity decreased with increasing temperature and could be described satisfactorily by a modified form of Bernoulli's equation. This relationship should also be valid for hydraulic cavitation in other geometries. However, since the value of the critical velocity may depend on the local surface texture, and thermodynamic properties of the fluid, its use as a tool for predicting incipient cavitation in untested situations appears to be limited. Although these data give additional support to the vortex-turbulence theories of nucleation, the exact mechanisms of creating clouds of bubbles from turbulence remains rather obscure.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 119.)

CAVITATION EFFECT ON THE DISCHARGE COEFFICIENT OF THE SHARP-EDGED ORIFICE PLATE

Numachi, F., Yamabe, M., and Oba, R. (Tohoku Univ., Sendai, Japan, Eng. Dept.)
J. Basic Eng. 82, 1-11 (1960)

This paper reports the experimental results of an investigation to determine the effects of cavitation on the discharge coefficient of sharp-edged orifice plates with reference to various degrees of cavitation as defined by a cavitation number. Water was the test liquid in these experiments. The experimental data described in this paper substantiate the fact that cavitation can exist to a minimum cavitation number of 0.2 without introducing errors in the orifice discharge coefficient in excess of the normal expected accuracy. In addition, it was also found that the use of air-inhalation to suppress the vibration and noise from the cavitation had no effect on the discharge coefficient. The earlier work of Richards, et al., showed that sharp edged orifices may be used for the measurement of the flow of liquid nitrogen and liquid hydrogen with the same confidence as with cold water, provided the same care is taken with the liquefied gases. The results of these orifice studies indicate that an orifice meter may be used to accurately measure liquid oxygen flow rates even if limited cavitation were present downstream of the orifice plate; the flow upstream of the orifice must be non-cavitating.

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Key words: Accuracy; air-inhalation; cavitation; Cavitation Numbers; discharge coefficients; flow measuring instruments; incipient cavitation; instrumentation; liquid hydrogen; liquid nitrogen; liquid oxygen; noise; noise suppression; orifice flow; orifice meters; orifices; Reynolds number; vibrations; water.

METHOD FOR PREDICTION OF PUMP CAVITATION PERFORMANCE FOR VARIOUS LIQUIDS, LIQUID TEMPERATURES, AND ROTATIVE SPEEDS

Ruggeri, R. S., and Moore, R. D. (National Aeronautics and Space Administration, Cleveland, Ohio, Lewis Research Center)

NASA Tech. Note D-5295 (Jun 1969)

A method that predicts the cavitation performance for centrifugal pumps and inducers is presented. This method, which is based on a developed cavity model, gives reliable results for liquid hydrogen, water, butane, freon, and methyl alcohol. Because the above liquids have such widely diverse physical properties, this technique should also apply to liquid oxygen. The predictive equations work so long as the pump geometry, the flow coefficient, and the cavitation number (based on minimum cavitation pressure) are maintained constant. Prediction of the complete cavitation curve (head-rise coefficient vs NPSH) for various temperatures and rotative speeds is also possible with this method. Its use requires two complete sets of reference cavitation data for each pump, one of which exhibits "thermodynamic effects" or pressure depressions below the saturated liquid pressure. These reference data need not necessarily be for the same liquid, liquid temperature, or rotative speed. This method represents the current state of the art of predicting cavitation performance in centrifugal pumps and inducers. In order to avoid ambiguity of various predictive methods (in other abstracts), this predictive technique will be referred to as the RMG method since the development of this method is credited to R. S. Ruggeri, R. D. Moore, and T. F. Gelder of NASA-Lewis Research Center, Cleveland, Ohio.

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Key words: Butane; cavitation; cavitation curves; Cavitation Numbers; centrifugal pumps; equations; flow coefficient; freon; inducers; liquid hydrogen; liquid oxygen; methyl alcohol; NPSH; predictive methods; pump cavitation; pumps; water.

CONDITIONS FOR MODELING CAVITATION PHENOMENA IN PUMPS FOR REFRIGERATION LIQUIDS

Barenboim, A. B.

Translated from "Refrigeration Techniques and Technology," 1, 95-103 (1965)

The author starts with the general equations of energy, momentum, continuity, and equation of state for the liquid and vapor phases which characterize the motion of two-phase flow. From these equations a system of criteria are obtained which describes the similarity of cavitation phenomena in geometrically similar pumps. Because it is not possible to satisfy all the above criteria simultaneously, this system of criteria is reduced to only a few which are judged to be the most important in the description of cavitation. The functional form of these criteria must be determined empirically. In this paper, the results of Salemann's experiments with refrigerant-11, water, butane, and benzol are used to test the similarity analysis. These data are well correlated using two of the above criteria — i.e., the Euler number (which contains NPSH) versus the Reynolds number (based on inlet tip speed) and a dimensionless grouping of the properties of the liquid and the vapor. More recent application of the author's correlating terms to centrifugal pumps also gives fairly good results. All of the above data are for 3 percent head dropoff and for centrifugal pumps running at a single speed. The development of the similarity conditions for geometrically similar pumps is not dependent on the type of pump and therefore should be valid for inducers as well as for centrifugal pumps, and with liquid oxygen as well as the previously mentioned fluids. However, the shape of the Euler-Reynolds curves may depend strongly on the pump operating conditions and geometry. Considerably more cavitation data are needed with various speeds, pump sizes, and types of pumps before the final correlating parameters used by the author can be accepted as being universal.

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Key words: Benzene; butane; cavitation; centrifugal pumps; equations; Euler number; Freon 11; geometry effects; heat of vaporization; inducers; liquid oxygen; mathematical models; NPSH; oxygen pumps; pump cavitation; pumps; Reynolds number; similarity analysis; similarity criteria; specific heat; two-phase; viscosity; water.

DESIGN STUDY OF LIQUID OXYGEN PUMPING SYSTEMS FOR MISSILE FUELING INCORPORATING VENTED STORAGE TANKS

Carter, Jr., T. A., and Crusan, C. R. (Turbocraft Co., Pasadena, Calif.)

Advan. Cryog. Eng. 4, 218-30 (1960)

A regeneratively fed jet pump and a centrifugal mainstage pump combination is described. This combination is believed to be capable of handling large flow rates of liquid oxygen with low values of pressure in the storage tank. Equations describing this type of operation are developed for the case of incipient cavitation in the jet. From this analysis the optimum combination of jet pump and centrifugal pump can be described. Additional flow through the centrifugal pump is required due to the recirculated drive fluid required by the jet pump. According to the authors' analysis this additional flow is detrimental to pump operation but is outweighed by the beneficial effect of increased suction pressure at the centrifugal pump due to the jet pump. Cavitation limit curves are constructed from theoretical equations. Experimental data are not reported.

Key words: Cavitation; cavitation curves; centrifugal pumps; efficiency; flight vehicle; head losses; incipient cavitation; jet-centrifugal pumps; jet pumps; liquid oxygen; oxygen pumps; oxygen systems pumping systems; performance curves; pump cavitation; pump design; pump parameters; pumps; pump pipings and fittings; storage; storage tanks; suction specific speed; tankage.

COMPARISON AND CORRELATION OF CENTRIFUGAL PUMP CAVITATION TEST RESULTS HANDLING LIQUID OXYGEN AND WATER

Carter, Jr., T. A., Crusan, C. R., and Thodal, F. (Turbocraft Co., Pasadena, Calif.)

Advan. Cryog. Eng. 4, 255-63 (1958)

Results of two pumps tested in water near room temperature, and in liquid oxygen, are reported. One pump is a two-stage, medium pressure, liquid oxygen transfer pump designed for 35 gpm and a 600 ft. head rise at 8400 rpm. An inducer (designed for a suction specific speed of 25,000) is employed in front of the first stage impeller. The second pump is a single-stage transfer pump. Its operating point is 150 gpm with a 125 ft. head rise at 3500 rpm. The cavitation performance with liquid oxygen was found to be better than that obtained with water. With the water data, a predictive technique using calculated B-factors is used by the authors to estimate the liquid oxygen NPSH at the fully cavitating point.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 128.)

ANALYSIS OF SINGLE AND TWO-PHASE FLOWS IN TURBOPUMP INDUCERS
Cooper, P. (TRW, Inc., Cleveland, Ohio)
J. Eng. Power, 89, 577-88 (1967)

A model is developed for analytically determining pump inducer performance in both the single-phase and cavitating flow regimes. The author's thesis is that in describing pump cavitation performance, both the thermodynamic properties of the fluid and the basic suction and flow parameters are necessary. Dimensional analysis of the governing equations yields suction and vaporization parameters from which correlations of solutions of these equations and of test results can be made. The parameters the author derives are not new and are those commonly used to describe similarity of cavitation in turbomachinery. A solution of the governing equations for the fluid velocities, pressures, and density distributions is required to evaluate a particular inducer design. Solutions of the equations for the condition of two-phase flow in the inducer inlet showed that little head deterioration resulted. More recent analytical work supports this conclusion. In the theory for NPSH requirements the author uses the assumption that for a given value of head drop-off and flow coefficient, the B-factor is constant. This assumption is subject to substantial variation and neglects changes in the B-factor which can occur with the same flow coefficient, but at different rotative speeds. It is suggested, in the discussion portion of this paper, that the two-phase Mach number be used as a basic correlating parameter rather than the B-factor. However, as the author points out, the Mach number is proportional to the square root of the B-factor. Thus, the use of Mach number should not give vastly different correlations. More work is definitely needed along the lines of analyzing the cavitating inducer performance based on both geometrical parameters and the thermodynamic effects. Recent experimental work with inducers shows that tip clearance can be an important parameter of the suction performance. Another complication to describe theoretically is the experimental fact that when an inducer is followed by a different main stage impeller, the suction performance of the inducer and hence the pump is usually different.

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Key words: B-factors; cavitation; critical (choking) two-phase flow; critical flow; equation of state; hydrogen; impellers; Mach number; mathematical model; nitrogen; NPSH; oxygen; pump cavitation; pump inducers; pump parameters; pumps pipings and fittings; Reynolds number; single phase flow; turbopumps; two-phase flow; vaporization; water.

JET PUMP CAVITATION

Cunningham, R. G., Hansen, A. G., and Na, T. Y. (Pennsylvania State Univ., University Park, Pa., Dept. of Mechanical Engineering)

ASME Winter Annual Meeting, Los Angeles, Calif., Nov. 16-20, 1969, Paper No. 69-WA/FE-29

Mixing-throat cavitation in a liquid jet pump results from high jet velocities, low suction (NPSH) pressure, or low discharge pressure. Incipient cavitation at the jet boundary has no effect on jet pump efficiency, but under severe conditions it spreads to the walls. A limiting flow condition results which is independent of discharge pressure. Efficiency deteriorates rapidly and the pump head-flow characteristics can no longer be predicted by conventional theory.

Eight correlation parameters (1937-1968) and their interrelations are examined. A Cavitation Index σ_L is recommended for correlation of cavitation-limited flow results. Limiting flow data from 14 references on water, oils, and mercury, plus additional data on three water jet pumps are compared, showing that 11 sets of data on water, oils, and mercury can be represented by the single-number index σ_L, with a range of 0.8 to 1.67. Conventional jet pumps are described by σ_L = 1.0 to 1.4 and σ_L = 1.35 is recommended for conservative use. The limiting flow function Y (NPSH) is shown to be a useful tool in comparing cavitation response to design changes.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A MORE DETAILED ABSTRACT, SEE PAGE 129.)

DETERMINATION OF NPSH ON LARGE CENTRIFUGAL PUMPS AND THOMA'S LAW OF SIMILARITY

Fang, K. S., and Koolhof, F. (FMC Corp., Los Angeles, Peerless Pump Div.)

1971 Cavitation Forum, Proc. 1971 Fluids Engineering Conf., May 10-12, 1971, Pittsburgh, Penn. American Society of Mechanical Engineers, New York, N.Y.

Cavitation performance of geometrically similar pumps at a one percent head or efficiency dropoff (whichever occurred first) are compared. The authors find that the Thoma number — NPSH/H, where H is the developed head — tends to increase with increasing size of the pump. The present data are not sufficient to generalize this apparent size effect and the difference in size alone may not be responsible for all the discrepancies. Although the data show that water rather than liquid oxygen was used here, care must be taken in extrapolating cavitation performance of a smaller size, model pump to the prototype. More pump cavitation scaling data are needed.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 126.)

SCALE EFFECTS ON CAVITATION
Holl, J. W., and Wislicenus, G. F. (Nebraska Univ., Lincoln, Nebr.)
J. Basic Eng. 83, 385-98 (1961)

The classical theory of similarity of cavitation expressed by $2(P-P_v)/\rho V^2$ Constant [where P is the static pressure in a uniform flow upstream of the cavitating object, P_v is the vapor pressure, and V the average upstream flow velocity] states that the cavitation conditions (the form and extent of cavitation voids) in two similar machines or structures with similar flows will be similar. The intent of this paper is to focus attention on the knowns and unknowns of the departures from this classical similarity law of cavitation, i.e., scale effects. A review of the similarity conditions, some experimental data with cold water with submerged flow models (which shed light on the scale effects), and attempts to correlate the above information are presented. In the discussion of scale effects the authors choose to distinguish between effects external to the boundaries of the cavitation voids and effects on the cavitation process itself. The effects of Reynolds number, Froude number, and Mach number are classified as the former, and the effects of the ratio of the vapor pressure to free stream pressure, the ratio of the cavity pressure depression below vapor pressure to free stream pressure, and Weber number, as the latter. The data used in the correlations in this paper are of the desinent point which is a very limited form of cavitation. A significant point in the discussion of this paper is that the conditions in the liquid environment would probably be altered rather significantly once cavitation has occurred. Hence a more realistic approach would be to determine scale effects with developed cavitation.

This paper was written before much of the cavitation data using liquid hydrogen, liquid nitrogen, and other liquids which have relatively strong thermodynamic effects were published. A result of this latter work has been a more general cavitation parameter based on the minimum static pressure (P_c) of the cavity; i.e., $2(P-P_c)/\rho V^2$ = Constant, where $P_c \leq P_v$. The authors conclude that the process of cavitation and its scale effects are not properly understood and that further, careful experimentation and analyses are needed. The same statement could be made today, approximately 11 years later. In the discussion of this paper, it is also emphasized that similarity arguments not based on physical observations are likely to be inappropriate and experiments which delineate the type of cavitation flows are necessary before meaningful similarity arguments can be made.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 127.)

TABULATED VALUES OF CAVITATION B-FACTOR FOR HELIUM, H_2, N_2, F_2, O_2, REFRIGERANT 114, AND H_2O

Hord, J., and Voth, R. O. (National Bureau of Standards, Boulder, Colo., Cryogenics Division)

Nat. Bur. Stand. (U.S.) Tech. Note 397 (1971)

A brief history is given on the development of the B-factor concept and its application to the design of liquid pumps. [B-factor is defined as the ratio of the volume of vapor to the volume of liquid involved in the cavitation process]. The results of the majority of cavitation research show that a change in thermodynamic properties of the fluid (achieved by changing fluids or changing the temperature of the same fluid) affects its cavitation qualities. Adaptation of the "quasi-static" vaporization model to the cavitation process is discussed; previous methods of computing B-factor are reviewed and a simplified, more precise computation, consistent with the "quasi-static" model, is established. Merits of different computational techniques are discussed and two of the methods are graphically compared. The best available property data are used to compute B-factors for several fluids over a wide range of temperatures. The results, tabulated as reference data, are useful in the application of pump cavitation predictive methods which require an accurate estimation of the B-factor. The units of the tabulated values of pressure and temperature depressions below the saturation curve are given in psi and degrees R, respectively. The fraternity of pump engineers has adopted the term "head" which requires knowledge of the liquid density for a given pressure and temperature. Thus, the tabulated values of the pressure depression must be converted if "head" depressions are desired.

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Key words: B-factors; cavitation; density; freon 114; liquid fluorine; liquid helium; liquid hydrogen; liquid nitrogen; liquid oxygen; mathematical models; pressure depression; pump cavitation; pumps; temperature depression; temperature effects; vaporization; water.

ON THE MECHANISM OF HEAD BREAKDOWN IN CAVITATING INDUCERS
Jakobsen, J. K. (Rocketdyne, Canoga Park, Calif.)
J. Basic Eng. 86, 291-305 (1964)

The mechanism of head breakdown in cavitating inducers, as affected by thermodynamic properties of the pump fluid and scale effects, is discussed. Results of some early cavitation tests on three different pumps, performed with water, liquid oxygen, and nitrogen are reported. These data are for a one percent head dropoff. The test results show a significant increase in suction performance when liquid oxygen (and liquid nitrogen) is used rather than water as the pump fluid. More recent liquid oxygen cavitation data with two similar pumps and two flow rates (the design flow rate and the design flow rate plus 17 percent) are reported for a two percent head dropoff. The data of Carter, Jr. and Crusan and the above are the only liquid oxygen pump cavitation data found (by the reviewer) in the open literature. The values of NPSH for the above conditions are correlated with a critical vapor fraction, derived from a local, unity Mach number condition. The correlation gives support to the author's proposed mechanism of head breakdown but is developed from data obtained from a relatively narrow range of flow coefficients, a single pump geometry, a single value of the percent head dropoff, and a single pump rotative speed. Another difficulty in the use of this theory is the uniqueness of the expression for the two-phase acoustic velocity; i.e., several other expressions are available which would give substantially different values of the two-phase acoustic velocity for the same conditions.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 131.)

TESTING PUMPS IN AIR
King, J. A. (Rocketdyne, Canoga Park, Calif.)
J. Eng. Power 90, No. 2, 97-105 (1968)

Rocket pumps, designed for operation with liquid oxygen and hydrogen have been tested with air. A good correlation of non-cavitating pump performance was found between the air and cryogenic liquids. Thus, the air data could be used to predict the pump performance in liquid oxygen (and hydrogen or other fluids). In the preinduced pumps tested in air, the static pressure at the inducer exit was found to be a useful indication as to whether the pump cavitates. As pointed out in the discussion in this paper, this testing technique is not new and its application requires some initial testing to verify an accurate correlation of the liquid and air data. Reynolds number effects can also be a problem and need to be considered in the testing analysis. The cavitation incipient point of some turbines has been previously predicted from blade pressure measurements in air. Prediction of developed cavitation performance with air tests is believed to be invalid. Although there are some shortcomings, testing liquid oxygen pumps in air is less expensive, safer, serves as an excellent tool for comparing changes in pump design, and can give some insight into the cavitation performance.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 132.)

TURBULENCE DEPENDENCE OF VAPOROUS CAVITATION IN OXYGEN JET

Nishigaki, K., Kato, E., and Saji, Y. (Kobe University of Mercantile Marine, Higashinada-ku, Kobe)

Jap. J. Appl. Phys. 8, No. 12, 1540-5 (Dec 1969)

For the purpose of clarifying the cavitation characteristics and the effect of turbulence on the inception of hydraulic cavitation, liquid oxygen and an oxygen-argon solution were cavitated in a liquid-liquid jet in the temperature range from 70 K to the normal boiling point under various hydrostatic pressures. A controlled differential pressure caused the liquid to flow through a nozzle submerged in the same liquid. At a certain "critical" value of the flow velocity, clouds of visible size bubbles appeared near the jet boundary (away from any solid surface). The first author reported in an earlier paper that choking of the nozzle was coincident with this incipient point, which is similar to the Mach one condition in the flow of compressible fluids. The critical velocity for liquid oxygen was found to be about 24.8 m/s. It was also found that the critical velocity decreased with increasing temperature and could be described satisfactorily by a modified form of Bernoulli's equation. This relationship should also be valid for hydraulic cavitation in other geometries. However, since the value of the critical velocity may depend on the local surface texture, and thermodynamic properties of the fluid, its use as a tool for predicting incipient cavitation in untested situations appears to be limited. Although these data give additional support to the vortex-turbulence theories of nucleation, the exact mechanisms of creating clouds of bubbles from turbulence remains rather obscure.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 119.)

METHOD FOR PREDICTION OF PUMP CAVITATION PERFORMANCE FOR VARIOUS LIQUIDS, LIQUID TEMPERATURES, AND ROTATIVE SPEEDS

Ruggeri, R. S., and Moore, R. D. (National Aeronautics and Space Administration, Cleveland, Ohio, Lewis Research Center)

NASA Tech. Note D-5295 (Jun 1969)

A method that predicts the cavitation performance for centrifugal pumps and inducers is presented. This method, which is based on a developed cavity model, gives reliable results for liquid hydrogen, water, butane, freon, and methyl alcohol. Because the above liquids have such widely diverse physical properties, this technique should also apply to liquid oxygen. The predictive equations work so long as the pump geometry, the flow coefficient, and the cavitation number (based on minimum cavitation pressure) are maintained constant. Prediction of the complete cavitation curve (head-rise coefficient vs NPSH) for various temperatures and rotative speeds is also possible with this method. Its use requires two complete sets of reference cavitation data for each pump, one of which exhibits "thermodynamic effects" or pressure depressions below the saturated liquid pressure. These reference data need not necessarily be for the same liquid, liquid temperature, or rotative speed. This method represents the current state of the art of predicting cavitation performance in centrifugal pumps and inducers. In order to avoid ambiguity of various predictive methods (in other abstracts), this predictive technique will be referred to as the RMG method since the development of this method is credited to R. S. Ruggeri, R. D. Moore, and T. F. Gelder of NASA-Lewis Research Center, Cleveland, Ohio.

(FOR LISTING OF IMPORTANT REFERENCES, KEYWORDS AND A DUPLICATE ABSTRACT, SEE PAGE 135.)

INVESTIGATION OF TWO-PHASE HYDROGEN FLOW IN PUMP INLET LINE

Urasek, D. C., Meng, P. R., and Connelly, R. E. (National Aeronautics and Space Administration, Cleveland, Ohio, Lewis Research Center)

National Aeronautics and Space Administration Tech. Note D-5258 (Jul 1969)

An investigation was conducted to evaluate the vapor-to-mixture volume ratio present in the inlet line of a pump when liquid hydrogen is pumped in a boiling condition in a sealed tank. An iterative solution of a simple one-dimensional model is used to predict the vapor-to-mixture volume ratios at various values of bulk fluid temperature. Experimental values of the vapor-to-mixture volume ratios are obtained indirectly and are compared with the predicted values. The good agreement obtained between the experimental and analytical results indicates that the vapor-to-mixture volume ratio can be predicted with reasonable accuracy. This method is not restricted to liquid hydrogen and can be used for liquid oxygen. The estimated values of vapor-to-mixture volume ratio, when used with previously reported results, may be useful in predicting pump inducer performance with two-phase flow.

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Key words: Analytical model; boiling; cavitation; flow rates; hydrogen; missiles and rockets; NPSH; pump inducers; pumps pipings and fittings; quality; spacecraft; spacecraft tankage; turbopumps; two-phase flow; vapor pressure; vaporization.

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