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SURVEY OF HEAT TRANSFER TO NEAR-CRITICAL FLUIDS

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16. Abstract

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SUMMARY

This report surveys near-critical heat transfer, including the following areas: thermal properties; heat-transfer boundaries of the near-critical region; free, natural, and forced convection experiments; oscillations; geometric effects; parameters which appear to be significant to heat transfer in the critical region; and theories which have been proposed for the region.

The report points out that the state of the art is such that completely satisfactory theories or correlations are not available for heat transfer in the critical region. It does, however, indicate the most promising and widely used correlations and suggests procedures for approaching a critical-point heat-transfer problem.

INTRODUCTION

Transport processes, particularly heat transfer, in the near-critical region have been of interest for about the last 15 years. Current emphasis stems from applications which require the use of a fluid in the near-critical condition, from inadequate information to produce satisfactory design expressions, and from an inadequate understanding of the mechanics which produce the peculiar behavior in the near-critical region.

Applications which are current or proposed include the use of near-critical helium to cool the coils of superconducting electromagnets and superconducting electronic or power-transmission equipment, the use of supercritical hydrogen as a working fluid or fuel for both chemical and nuclear rockets; the use of supercritical water in electricity generating plants, and the use of methane as a coolant and fuel for the supersonic transport.

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Before and during World War II, Ernst Schmidt and his associates conducted research in heat transfer by natural convection. They found the heat-transfer coefficient for a near-critical fluid to be quite high, because the specific heat and the compressibility both appeared to approach infinity at the critical point. The application they had in mind was the cooling of turbine blades in the then new jet engines.

In the mid-1950's, a substantial number of papers began to appear which reported a rather wide range of results and proposed mechanisms underlying some of the unique heat-transfer behavior. Several authors suggested that the heat-transfer characteristics of a fluid near its critical point resembled boiling. This idea persists in the literature today, but the extent and influence of this boiling-like behavior still remains to be finally established. The dominant near-critical working fluids have been hydrogen, water, carbon dioxide, Freons, and ammonia.

The reported research may be divided into two broad classes: forced and natural convection in heated tubes, and free or natural convection from heated wires and flat plates. The first class provided experimental turbulent-heat-transfer data for use in design and in establishing the reliability of correlations and theoretical analyses. The second class of studies focused more attention on the detailed mechanisms. The data from both these studies showed substantial contradiction, but there is an ever-increasing understanding of the conditions likely to produce such contradictions.

Theoretical heat-transfer analyses have not been very successful; however, this approach still shows promise in unravelling the mysteries of the near-critical region. By contrast, flow oscillations, characteristic of this region, have been examined analytically and found to be reasonably well predicted by using rather conventional concepts in mechanics.

This report surveys near-critical heat transfer, including the following areas; thermal properties; heat-transfer boundaries of the near-critical region; free, natural, and forced convection experiments; oscillations; geometric effects; parameters which appear to be significant to heat transfer in the critical region; and theories which have been proposed for the region.

The report is written with a twofold purpose: The first is to bring the information in this region together and to examine these data from a designer's point of view. The second is to examine the flow mechanisms underlying the behavior. Within the limitations of knowledge in this field, this examination lends itself not so much to selection of prime variables influencing the flow, but, more to recommendations for future work in the area.

Since this is a survey report, the authors are indebted to the entire community of researchers in the fields of near-critical heat transfer and near-critical thermodynamics for the material presented herein. In particular we are indebted to several individuals who made available their original figures for use in this report. They are

NEAR-CRITICAL FLUID PROPERTIES

Thermodynamics of the Critical Point

The exceptional heat-transfer behavior of a near-critical fluid must ultimately be due to the influence of the unusual property behavior of a fluid near its critical point, as shown in figure 1. This is manifested both in the changes of the thermal properties themselves, and in the modifications of the flow structure caused by these changes. For any analysis to succeed, a good knowledge of the thermal properties is required.

The classical approach to the thermodynamics of the critical point is well documented in Hirschfelder, Curtiss, and Bird (ref. 1) and in Rowlinson (ref. 2). For excellent surveys of some of the more recent ideas, the reader is referred to Hammel (ref. 3), Widom (ref. 4), and Sengers and Levelt Sengers (ref. 5).

The Van der Waals equation of state

$$P = \frac{\rho \mathcal{R} T}{1 - b_1 \rho} - a_1 \rho^2 \tag{1}$$

where a_1 is an attraction force constant and b_1 is a repulsion force constant, is representative of the classical approach. (All symbols are defined in appendix A.) Among other things, at the critical point the Van der Waals equation (eq. (1)) yields an infinite specific heat at constant pressure and an infinite thermal expansion coefficient $(-\partial \ln \rho / \partial T)_P$, which Schmidt (ref. 6) cited as reasons why the critical fluid was an attractive heat-transfer medium.

The Van der Waals equation of state (eq. (1)) yields a cubic curve for the critical isotherm on the pressure-density (P-ρ) plane and a quadratic for the coexistence curve. In reality (ref. 3), the critical isotherm is more nearly fifth degree, and the coexistence

(a) Thermodynamic properties.

(b) Transport properties.
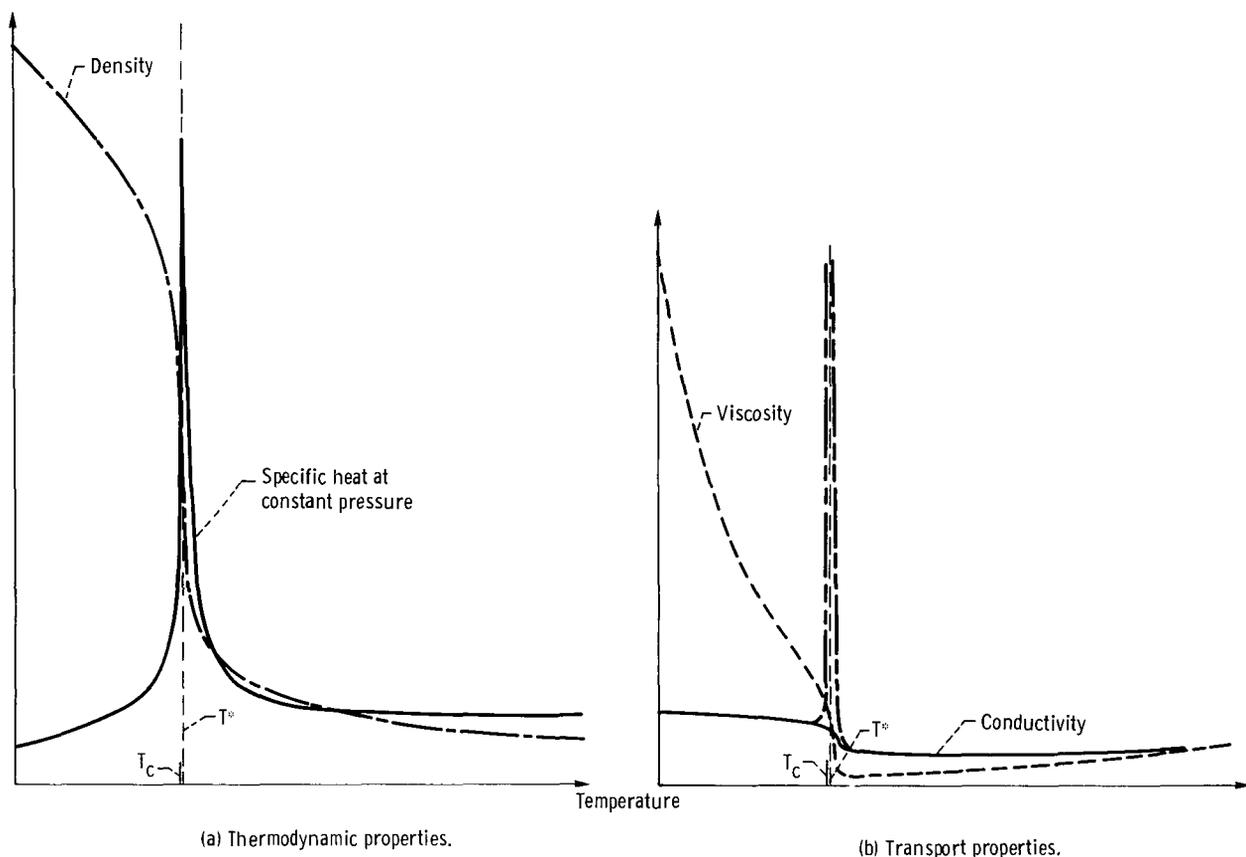
Figure 1. - Typical thermodynamic and transport properties of near-critical parahydrogen. Ratio of pressure to critical pressure, 1.05. (Data taken from refs. 10 and 17).

curve is almost a cubic. This does not affect the primary condition for determining the critical point, that of equal saturation densities. It does, however, interject uncertainty as to the nature of the higher derivatives of P with respect to ρ.

The Van der Waals equation also yields a finite discontinuity for the specific heat at constant volume C_v at the critical point. Experimental evidence by Bagatskii, et al. (ref. 7) indicates that C_v has a logarithmic infinity with a superimposed finite discontinuity along the critical isochore. Widom's recent qualitative survey of his activities (ref. 4) proposes a three-dimensional lattice gas model to account for these difficulties.

Since near-critical thermodynamic data are somewhat scarce, the heat-transfer investigator is likely to have to extrapolate from other regions or other fluids. This prompts a comment on the law of corresponding states. To a good first-order approximation, it can be said that the thermal properties of all fluids collapse to a single curve when normalized by the appropriate critical constants. There are some problems. The second-order deviations are more severe near the critical point. For spherical nonpolar gases such as hydrogen and nitrogen, Z_c = 0.304 and 0.292, respectively; whereas, for the polar molecule water, Z_c = 0.224, approximately a 25 percent difference.

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The hydrocarbons fall in between (ref. 1). When dealing in corresponding states, it is best to subdivide the fluids by molecular type. For quantum fluids, like helium, corresponding states should be avoided.

A final area of importance to heat transfer is the nonequilibrium phenomenon associated with the critical point. Maass (ref. 8) found that a hysteresis loop in density near the critical point could be obtained by first heating and then cooling along an isobar, as shown typically in figure 2. The results were very stable and reproducible even under
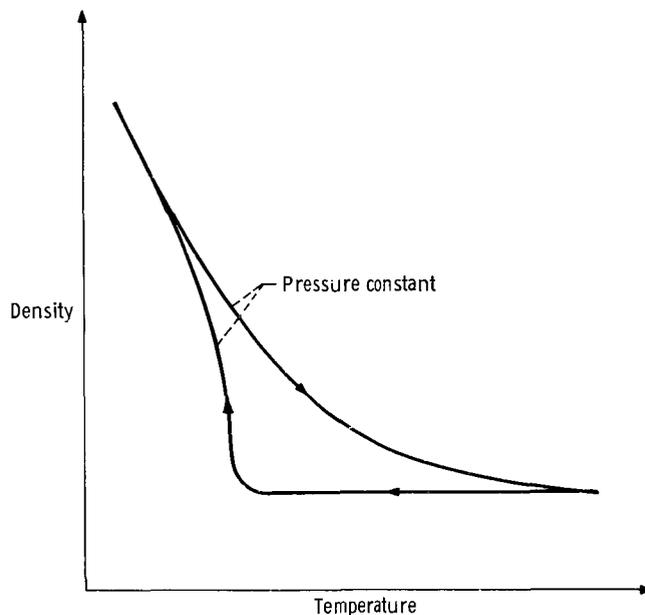
Figure 2. - Typical near-critical isobar exhibiting hysteresis loop according to Maass' experiment (ref. 8).

conditions of stirring. Another hysteresis example can be found in light scattering. Light scattering caused by severe density fluctuations near the critical point causes the fluid to become opaque as it passes through the critical point. The growth of the opaque condition, known as critical opalescence, is quite different depending on whether heating or cooling through the critical point is occurring. (For an excellent visual record of the critical opalescence phenomenon, the reader is referred to a motion picture produced by Siemens Aktiengesellschaft, Postfach, West Germany, entitled "Boiling and Evaporation Phenomena with Water.") These experiments demonstrate that, near the critical point, large relaxation times are required for a thermally disturbed system to return to equilibrium. One consequence of this is that the near-critical fluid under the dynamic conditions of heat transfer can be expected to experience some degree of thermodynamic nonequilibrium. This, in turn, will result in some uncertainty in applying an equation of state. In a private communication, Walter G. Zinman (Grumman Aircraft) argues

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that fluctuations are inherent to the thermodynamic critical point and that therefore the experimentalist may not be able to precisely locate such a point.

Also, since the paths are different, the heat-transfer process involved in cooling a near-critical fluid may be quite different than that associated with heating the same fluid.

Most of the truly severe behavior, such as the singularities in C_p, C_v, λ, and β_1, occur precisely on the critical point. Normally, operation is not precisely on the critical point. This will tend to attenuate the influence of some of the anomalies. On the other hand, the overall large property changes, the suggested first-order effect, persist over a considerable region near the critical point.

Pressure-Density-Temperature Data - Equations of State

The availability of actual P-ρ-T data near the critical point varies considerably from fluid to fluid. Probably the most detailed investigations near the critical point have been in carbon dioxide by Michels, Blaisse, and Michels (ref. 9) and in hydrogen by Goodwin, et al. (ref. 10). For other fluids of interest, like nitrogen, there is little, if any, actual data. For the most part, the heat-transfer researcher must rely on properties computed from an equation of state.

Equations of state come in all sizes and shapes. The most common are the virial type

$$P = A(T)\rho + B(T)\rho^2 + C(T)\rho^3 + D(T)\rho^4 + \ldots \tag{2}$$

Obert (ref. 11) and Hirschfelder, et al. (ref. 1) have good surveys. They list coefficients for various equations and fluids; however, they were not determined with the critical point specifically in mind. In cryogenic fluids, the Benedict-Webb-Rubin (ref. 12) equation of state, as modified by Strobridge (ref. 13) and Roder and Goodwin (ref. 14), has been very popular:

$$P = \Re T\rho + \left(\Re n_1 T + n_2 + \frac{n_3}{T} + \frac{n_4}{T^2} + \frac{n_5}{T^4}\right)\rho^2 + \left[\Re n_6 T + n_7 + \left(\frac{n_9}{T^2} + \frac{n_{10}}{T^3} + \frac{n_{11}}{T^4}\right)e^{-n_{16}\rho^2}\right]\rho^3$$

$$+ n_8 T\rho^4 + \left[\left(\frac{n_{12}}{T^2} + \frac{n_{13}}{T^3} + \frac{n_{14}}{T^4}\right)e^{-n_{16}\rho^2}\right]\rho^5 + n_{15}\rho^6 \tag{3}$$

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TABLE I. - SOURCES OF NEAR-CRITICAL PROPERTIES

Fluid	Critical constants			Source reference		Pressure-density-temperature, P-ρ-T	Properties recommended as computable by source authors						
	Pressure, P_c, atm	Temperature, T_c, K	Density, ρ_c, g/cm^3	Equation of state	Transport properties		Enthalpy, H	Specific heat at constant pressure, C_p	Specific heat at constant volume, C_v	Expansion coefficient, $\beta_1 = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p$	Entropy, S	Viscosity, η	Thermal conductivity, λ
Helium-4	2.26	5.3	0.0692	[a]22, 170	32, 33, 35	X	X				X	X	X
Hydrogen	12.80	32.99	0.0314	10, 14, 16, 17, 171, 172	26, 31, 33, 35	X	X	X	X	X	X	X	X
Nitrogen	33.5	126.2	0.311	13, 173	29, 33, 35	X	X					X	X
Oxygen	50.14	154.8	0.4358	174, 175	33, 35, 176	X	X	X	X	X	X	X	X
Methane	45.66	190.7	0.1625	15	27	X							
Propane	42.1	370.0	0.210	177	--------	X	X	X	X	X	X		
Kerosene	------	------	------	[b]178	--------								
Water	218.2	647.3	0.322	179 to 182	33, 35	X	X	X	X		X	X	X
Carbon dioxide	72.90	304.2	0.468	9, [a]22	24, 25, 30, 33, 35							X	X
Freon-12[c]	40.69	385.1	0.557	183	--------	X	X		X		X		
Freon-114	31.45	418.7	0.582	184	--------	X	X				X		
Ammonia	112.3	406.1	0.236	185	28, 33, 35, 185	X				X		X	X

[a]Limited range of application.
[b]No known equation of state.
[c]Decomposition potentialities near the critical point must be recognized when using this fluid.

An alternate form of the Benedict-Webb-Rubin (BWR) equation was used by Vennix (ref. 15) to correlate his near-critical-methane data. The coefficients are of a different type than equation (3), and the exponentials are linear in ρ and T. The main difficulty with these or any <u>curve-fit</u> equation is determining other properties, such as specific heat C_p, since this requires derivatives which are often not very satisfactory near the critical point. For specific discussions of accuracy, the reader is referred to the individual references (table I).

Table I lists source references for equations of state for the fluids discussed herein. The table includes an indication as to whether the particular authors suggest computation of other useful thermodynamic properties. In some cases, P-ρ-T are not used as primary variables. The table also lists transport properties. These will be taken up in the next section. For some fluids, such as hydrogen, entire computerized property packages are available (e.g., refs. 16 and 17 and a National Bureau of Standards (NBS) property package based on refs. 10 and 14).

Recently there has been considerable interest in the use of the Ising model for ferromagnets to describe the lattice gas near the critical point (refs. 18 and 19). This is discussed in the surveys (refs. 3 to 5) mentioned earlier. In drawing the analogy with the Ising model, chemical potential appears to be a more fundamental variable than pressure. Green and his co-workers (refs. 20 and 21) have offered the following equation, in which chemical potential is expressed as a function of density and temperature:

$$\frac{\dfrac{\left[\mu(\rho, T) - \mu(\rho_c, T)\right]\rho_c}{P_c}}{|t|^{\beta_2 \delta_1}} = |x_1|^{-\beta_2 \delta_1} h(x_1) \tag{4}$$

where $t = (T - T_c)/T_c$ and $x_1 = t / \left[(\rho - \rho_c)/\rho_c\right]^{1/\beta_2}$

In reference 21 the function $h(x_1)$ had yet to be determined analytically but could be seen graphically (fig. 3(a)). In a more recent paper (refs. 22 and 23), Vicentini-Missoni, Levelt Sengers, and Green have succeeded in developing a closed-form expression for $h(x_1)$

$$h(x_1) = E_1\left(\frac{x_1 + x_o}{x_o}\right)\left[1 + E_2\left(\frac{x_1 + x_o}{x_o}\right)^{2\beta_2}\right]^{\left[\beta_2(\delta_1 - 1) - 1\right]/2\beta_2} \tag{4a}$$

(a) Graphical representation of $h(x_1)$ (ref. 21).

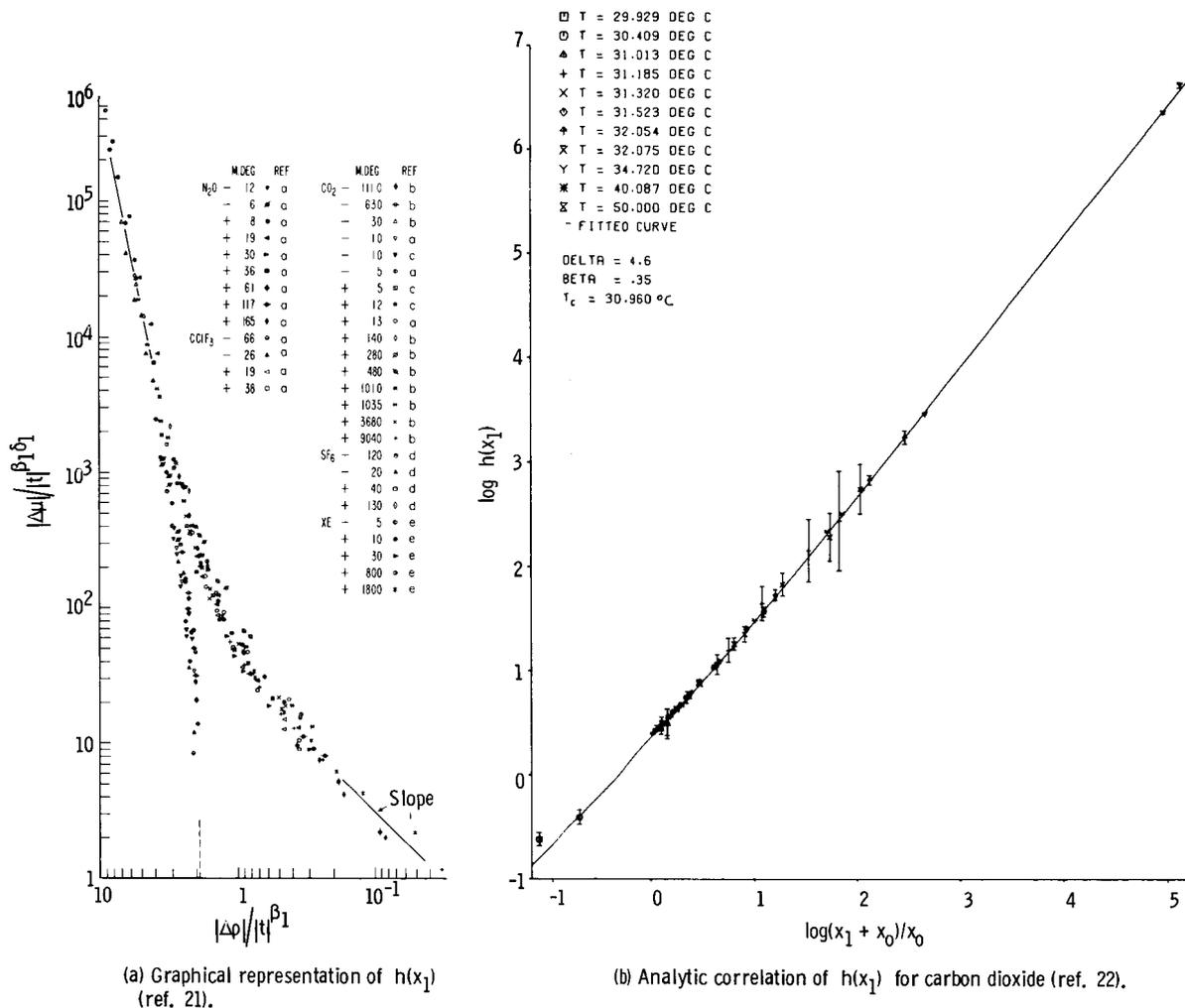(b) Analytic correlation of $h(x_1)$ for carbon dioxide (ref. 22).

Figure 3. – Scale-reduced chemical potential as function of scale-reduced density. (Data reproduced from refs. 21 and 22).

The results are shown for carbon dioxide in figure 3(b). Thus a closed-form equation of state is now available which is directed specifically at the critical region and which is subject to a very few adjustable constants, β_2, δ_1, E_1, E_2, and x_o. Of these, only x_o is very sensitive. Its major limitation is range. It is presently limited to ±30 percent in $\Delta\rho$ and $-0.01 < t < 0.03$. Thus in a practical property package, such as references 16 and 17, equations (4) and (4a) will have to be merged with the more common virial equations such as equation (3).

Transport Properties

Most of the remarks made concerning P-ρ-T data can be made about transport property data. Again, the more popular fluids are better documented. There are

near-critical thermal conductivity data for carbon dioxide by Sengers (ref. 24) and by Guildner (ref. 25), for hydrogen by Diller and Roder (ref. 26), for methane and ammonia by Sokolova and Golubev (refs. 27 and 28), and for nitrogen by Ziebland and Burton (ref. 29). Viscosity has been measured for carbon dioxide by Kestin, Whitelaw, and Zien (ref. 30) and for hydrogen by Diller (ref. 31).

Prior to Sengers' work, it was thought the excess of viscosity or thermal conductivity above its "atmospheric" value at a given temperature and pressure was a function of density alone:

$$\lambda(P, T) - \lambda^*(\rho \to 0, T) = f_1(\rho) \tag{5}$$

$$\eta(P, T) - \eta^*(\rho \to 0, T) = f_2(\rho) \tag{6}$$

where $f_1(\rho)$ and $f_2(\rho)$ may be determined to almost the critical temperature for a gas by a density variation of the form:

$$f_1(\rho) = \lambda_1 \rho + \lambda_2' \ln \rho + \lambda_2 \rho^2 + \ldots \tag{5a}$$

$$f_2(\rho) = \eta_1 \rho + \eta_2' \ln \rho + \eta_2 \rho^2 + \ldots \tag{6a}$$

Of course, this required a precise knowledge of ρ as a function of P and T; nevertheless, it allowed a very simple representation for viscosity and thermal conductivity. Furthermore, it could be reduced to general form by the law of corresponding states. This is still true away from the critical point, except possibly for quantum liquids such as hydrogen and helium (see refs. 26 and 32). The functional relations of equations (5) and (6) have been established for most fluids of interest by Thodos and co-workers and are summarized in a paper by Stiel and Thodos (ref. 33). Equations (5) and (6) remain valuable as a base line. In a private communication, H. J. Hanley of NBS, Boulder, Colorado, examined the hydrogen viscosity data of Diller (ref. 31) and interpreted the results to mean that there exists, at best, a weak anomaly; however, it does not occur at the critical density. Therefore, for viscosity the best evidence indicates only a weak anomaly, which can be disregarded for most fluid flow and heat-transfer calculations.

All the thermal conductivity data cited above exibit an "anomalous spike" in the conductivity at the critical density along near-critical isotherms, as shown in figure 4 (taken from ref. 34).
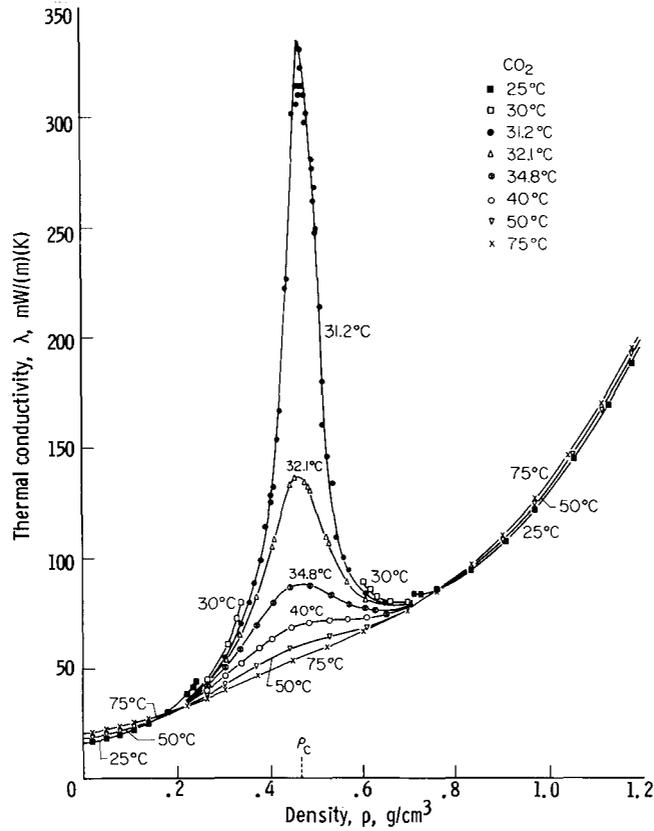
Figure 4. - Thermal conductivity of carbon dioxide exhibiting the anomalous spike. (Data reproduced from ref. 34).

The computation of the anomaly is still in developmental stages. Brokaw (ref. 35) suggests treating a near-critical fluid as a dissociating polymer and that conductivity consists of two parts

$$\lambda = \lambda_f + \lambda_r \tag{7}$$

Here λ_r represents the contribution due to diffusion of the dissociating clusters and λ_f the normal conductivity expressed by equation (5). The results of Brokaw's analysis are

$$\lambda_r = \rho D \, \frac{D_{1n}}{D} \left(C_p \right)_r \tag{8}$$

where D is the self-diffusion coefficient, D_{1n} is the binary diffusion coefficient of the hypothetical polymer, and $\left(C_p \right)_r$ is the specific heat in excess of the low-pressure value.
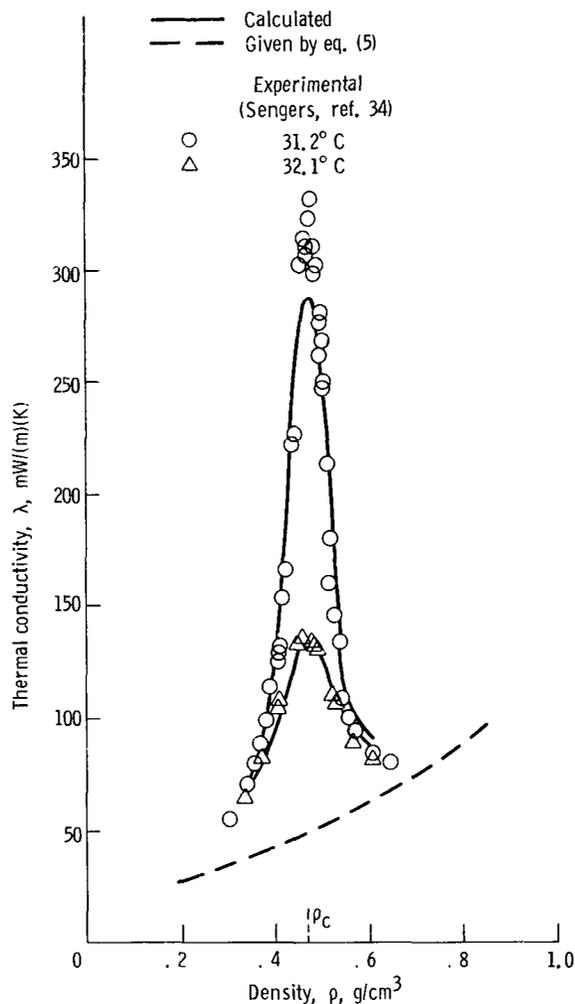
Figure 5. - Calculated and experimental thermal conductivities of carbon dioxide. (From ref. 35.)

Brokaw's calculations are compared to Sengers' data in figure 5. Unfortunately, the theory requires a good equation of state for computing $\left(C_p\right)_r$ and D_{1n}/D. So far it has not been tried for other fluids.

Even though the data of Diller and Roder (ref. 26) for hydrogen and the data of Hanley and Childs (ref. 32) for helium place in considerable doubt the dependence of $\lambda - \lambda_0$ on ρ alone, even away from the critical point, equation (5) will probably have to be treated as the best available in all cases, except for liquid hydrogen and helium.

For the present, we can recommend computation of thermal conductivity by equation (7) using equation (5) to obtain λ_f and by Brokaw's theory, where an adequate equation of state is available, for λ_r. Viscosity can be computed directly from equation (6).

Many additional related properties (vapor pressure, heat of vaporization, surface tension, and others) can be found in the NBS compendium by Johnson (ref. 36).

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Pseudocritical Properties

The unusual property behavior in the near-critical region shown on figure 1 can be examined as an extension of saturation properties.

Frequent reference is made in near-critical work to the transposed critical temperature T^*. This is normally defined as the temperature where the specific heat C_p attains a maximum for a given supercritical pressure (see fig. 1). The locus of the T^* points for hydrogen is shown in figure 6 and seems to be a very natural extension of the saturation curve. It is not, however, the same as an extension of the vapor pressure curve by the Clapeyron equation using enthalpy difference for latent heat (fig. 6) (refs. 37 and 38). Near the critical point, however, the T^* locus can be considered a pseudosaturation temperature. The T^* locus can be considered to approximately separate the pseudoliquid from the pseudovapor. Notice also on figure 6 that the T^* (or max C_p) effect has pretty well diminished at a P/P_c corresponding to the maximum in the Joule-Thompson inversion locus. Thermodynamically then, it can be said that the critical region is confined within the inversion locus.

In order to use pseudoboiling models, certain two-phase quantities in addition to the vapor pressure curve must be defined. Typical of these is latent heat of vaporization.
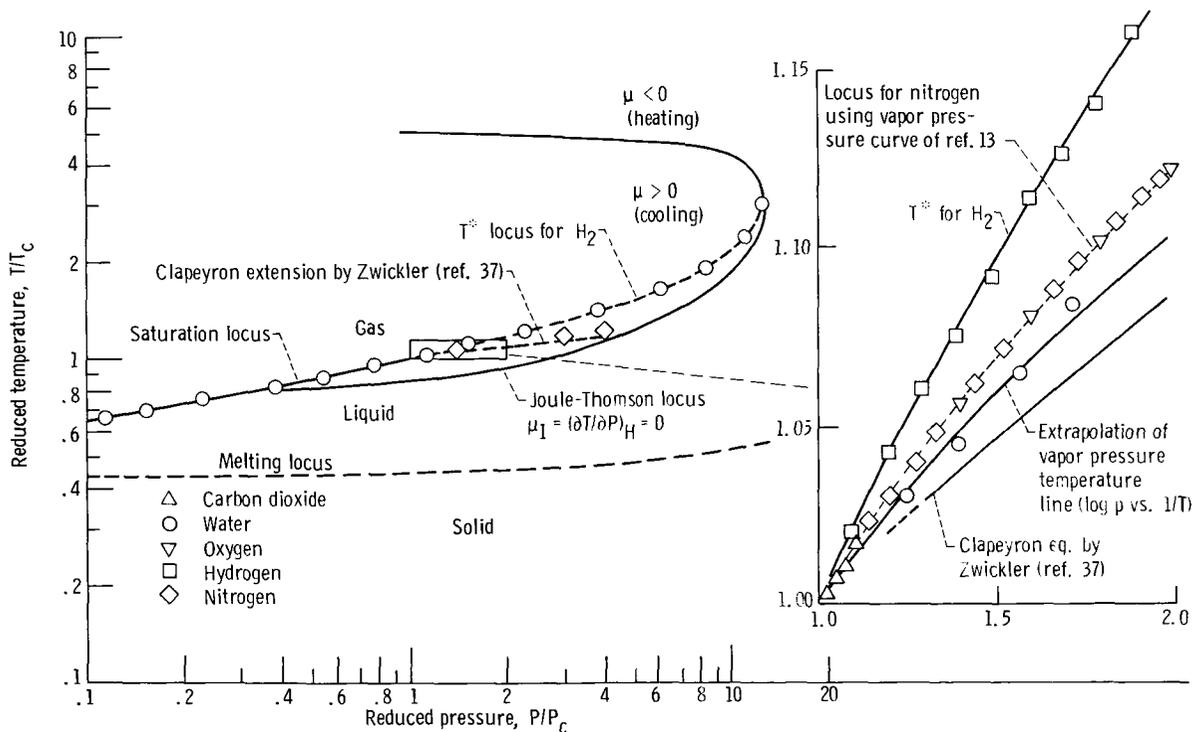

Figure 6. - Thermodynamic region of influence of the critical point on heat transfer. Basic locus is for hydrogen. (Clapeyron extension of saturation curve from ref. 37.)
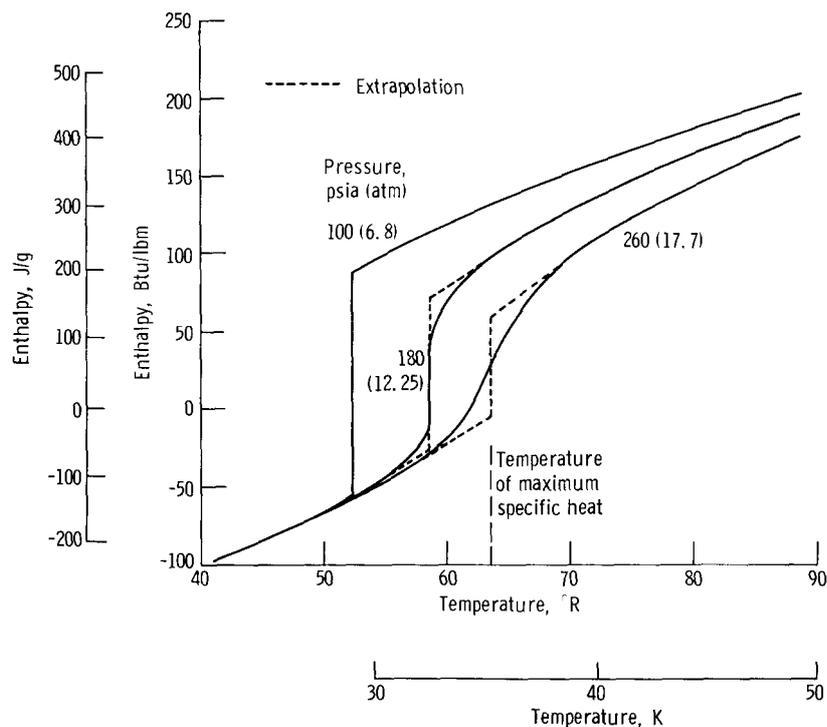
Figure 7. - Pseudo-two-phase properties; extrapolation procedure for equivalent latent enthalpy of vaporization. (From ref. 40.)

Figure 7 shows a way of defining a pseudoheat of vaporization from the enthalpy curves, as used by Thruston and others (refs. 39 and 40). Other pseudo-two-phase quantities, such as ''saturated'' liquid and vapor densities, can be approximated in the same way (refs. 41 and 42).

In summary we can say:

(1) Classical Van der Waals models do not accurately describe the state of a near-critical fluid, but may be satisfactory in first-order considerations.

(2) The discrepancies in the law of corresponding states are accentuated in the critical region, and the law should be used only between fluids of similar molecular structure.

(3) A thermally disturbed near-critical fluid requires long relaxation times to return to equilibrium.

(4) Equations of state of the conventional virial type can be made to accurately map a near-critical P-ρ-T surface; however, they are not good for thermal properties requiring derivatives of the equation of state.

(5) A new analytic equation of state involving chemical potential, density, and temperature, based on the Ising lattice gas model, has been developed for the near-critical region.

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(6) The evidence for the existence of a strong anomalous spike in thermal conductivity at the critical point is overwhelming. The spike can be estimated by treating the fluid as a dissociating polymer and superimposing the results on the conventional $\lambda - \lambda^* = f_1(\rho)$ curve (eq. (5)).

(7) If a similar spike occurs in viscosity, it is sufficiently weak to be ignored. Thus, $\eta - \eta^* = f_2(\rho)$ (eq. (6)) will adequately describe viscosity.

(8) Pseudo-two-phase thermal properties can be generated by extrapolation of saturation properties and relations into the near-critical region.

HEAT-TRANSFER REGIONS

The heat-transfer problem will be broken into four parts: gases (regions I and Ia), liquids (region II), and two phase (region III), which are the three regions adjacent to the critical region; and region IV, the near-critical region itself. These four regimes are illustrated in figure 8. Although this map is based on extensive hydrogen data, a
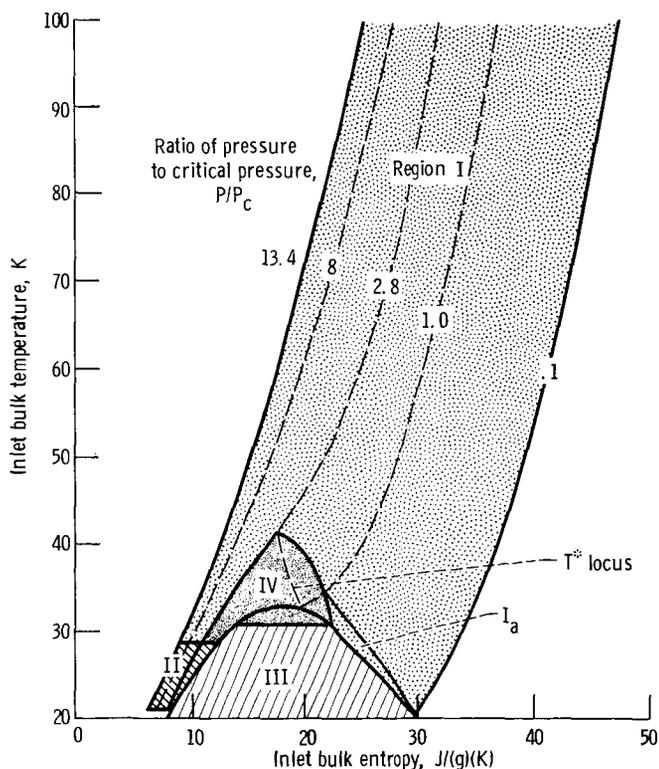

Figure 8. - Heat-transfer regions as function of inlet conditions. Region I, gas or fluid; region Ia, gas (low temperature); region II, liquid (fluid); region III, two phase; region IV, near critical.

similar map could be anticipated for other fluids. In order to determine the heat transfer and pressure drop, the region of interest must first be determined. Such a procedure is discussed and flow-charted in appendix B. In the following sections, before going to the near-critical heat-transfer problem (region IV), recommendations are offered for the adjacent regions I, Ia, II, and III.

Region I - Gas-Fluid

The data of McCarthy and Wolf (refs. 43 and 44) and Taylor (ref. 45) for hydrogen and helium give extensive heat-transfer and pressure-drop coverage of region I. The recommended equation is that of Taylor, which includes entrance effects and reduces to the successful equation of McCarthy and Wolf (refs. 43 and 44) at $X/d > 25$.

$$Nu = (Nu)_b \left(\frac{T_w}{T_b}\right)^{-(0.57 - 1.59 \, d/X)} \tag{9}$$

where

$$(Nu)_b = 0.023(Re)_b^{0.8}(Pr)_b^{0.4} \tag{10}$$

Taylor (ref. 46) and McCarthy and Wolf (ref. 44) also determined friction factor for the data of region I. The equation of Taylor is recommended. It approaches the classic equation of Koo-Drew and McAdams at low T_w/T_b. Taylor's equation is

$$\frac{f}{2} = \left(0.0007 + \frac{0.0625}{(Re)_w^{0.32}}\right)\sqrt{\frac{T_b}{T_w}} \tag{11}$$

Region Ia - Near-Saturation, Low-Temperature Gas

This region represents an extension of region I, with gas-like behavior and strong property variations. Perroud and Rebière (ref. 47) and J. Gladden of Lewis (personal communication) investigated pressures ranging from atmospheric to several atmospheres, with inlet temperatures near saturation. Perroud's equation is

$$(Nu)_b = 0.0032(Re)_b^{0.95}(Pr)_b^{0.4}$$

Taylor was able to correlate much of these data by using equation (9).

Region II - Liquids

Region II of the map (fig. 8) would be classified as liquid, with a process at low-to-moderate temperature differences. The conventional techniques of handling liquid heat transfer as given by McAdams (ref. 48), and also by equations (9) and (10), are expected to be valid (perhaps modifying the constant 0.023).

Region III - Two Phase

The two-phase regime, region III in figure 8, has been actively explored for many cryogens and noncryogens. Perroud and Rebière (ref. 47), Hsu, et al. (ref. 49), Giarratano and Smith (ref. 50), Hendricks, et al. (refs. 41 and 51), and others, have explored cryogens. Noncryogen works are extensively covered in a text by Tong (ref. 52).

Heat transfer to two-phase cryogenic fluids at high heat fluxes can be adequately correlated by the theoretical approach of Hsu, et al. (ref. 49) and the semiempirical approach of Perroud and Rebière (ref. 47). The latter is quiet similar to that of Hendricks, et al. (refs. 41 and 51). In most cases, the pressure drop is due to momentum changes, and friction pressure drop is difficult to assess.

Hsu, suggested that two-phase heat transfer could be treated with traditional single-phase correlations if the thermal and transport properties were weighted according to the void fraction; that is,

$$(Nu)_{\overline{\varphi}} = 0.023(Re)_{\overline{\varphi}}^{0.8}(Pr)_{\overline{\varphi}}^{0.4} \tag{12}$$

where

$$\overline{\varphi} = \alpha_l \varphi_l + \alpha_x \varphi_x$$

and φ represents any and all the fluid properties in equation (12). The reference condition x was determined empirically for hydrogen and, so far, has not been checked with other fluids (see ref. 49).

The equations given by Perroud have been applied to tubes and channels, as well as to several different cryogens. In all cases, the basic form remains the same:

$$(Nu)_{fm}(Sr)^{1/3} = f(\chi_{tt}) = a + \frac{d_1}{b + c\chi_{tt}} \tag{13}$$

however, the function $f(\chi_{tt})$ is altered slightly by differences in fluids and geometry (e.g., for hydrogen flowing through a tube, $a = 1.16$, $b = 0.16$, $c = 0.3$, and $d_1 = 1$; and for hydrogen flowing through a channel, $a = 1.08$, $b = 0.135$, $c = 0.20$, and $d_1 = 1.0$) (ref. 53).

Phenomenologically, at sufficiently high T_w/T_b values, vapor can be expected at the wall and fluid particles (filaments) in the core, while just the opposite is true for low T_w/T_b values. The occurrence of large temperature differences or large T_w/T_b is more natural in cryogenic fluids, and is one of the major reasons for the once prevalent opinion that heat transfer to cryogens and noncryogens differed. In both boiling and near-critical fluids, the range in $T_w - T_b$ or T_w/T_b is pertinent to heat transfer and will be considered more fully in the section NEAR-CRITICAL HEAT-TRANSFER REGION.

Boundaries of Region IV - Near-Critical Region

It is difficult to define the boundaries which separate the near-critical region (region IV) from its adjacent regions. There are several reasons for this: (1) For most fluids, the data are not sufficient; (2) the transition is not abrupt and sharp demarcations are difficult to determine; and (3) the near-critical influence will persist further into the adjacent regions, depending on the path (process) the fluid took to arrive at a given state point (see appendix A). This last point is particularly elusive. A gas can be precooled at critical pressure down to, and possibly even below, the transposed critical temperature T^*; and, when run in a heated-tube experiment, it will behave as a precooled gas (i.e., similar to region I). On the other hand, if liquid is heated up through region IV to the same state point in a heated tube, the results will be quite different. Part of the near-critical heat-transfer problem is how the fluid arrives at a given state point (i.e., prior history does make a difference). This is discussed more fully in appendix A.

Nevertheless, classification of the heat-transfer regions by state conditions is convenient, uesful, and generally reasonable. For hydrogen (as shown in fig. 8), the pressure boundaries are $0.8 < P/P_c < 3$. The lowest temperature boundary is T_{sat}, corresponding to $P/P_c = 0.8$, and the upper boundary is the vicinity of T^*, the transposed critical temperature. Other fluids have not been explored extensively enough to establish

their boundaries or to confirm the universality of the hydrogen boundaries. In the absence of data, the hydrogen boundaries can probably be taken as reasonable for other fluids.

A comment is in order here concerning boundaries. What is meant in establishing these boundaries is that outside of them the influence of the critical point can be considered to be negligible and conventional variable property correlations will prevail. It does not mean that in every case within region IV conventional methods will fail. Some combinations of parameters within region IV will be amenable to conventional approaches; but, in general, this region will require analyses directed specifically at the near-critical heat-transfer phenomenon.

The problem of heat-transfer regions can be summarized in the following manner:

(1) The near-critical heat-transfer region and its adjacent regions can be delineated in an approximate manner on a temperature-entropy state diagram.

(2) It is not possible to set precise near-critical heat-transfer boundaries for the following reasons:

(a) Data are generally insufficient.

(b) The transition from region to region is not abrupt.

(c) Most important, the extent of influence of the critical point on heat transfer is a function of the process (or path) by which the fluid approaches the critical point.

(3) Heat transfer in the adjacent regions can be correlated by conventional methods appropriate to that region. In fact, the correlatable nature of the adjacent regions helps determine the near-critical boundaries.

NEAR-CRITICAL HEAT-TRANSFER REGION

Pecularities of the Near-Critical Region

In region IV (fig. 8), standard techniques of correlating data break down. The ordinary Dittus-Boelter equation (eq. (10)) does not correlate near-critical forced convection phenomena; ordinary Rayleigh relations do not correlate pool data; standard boiling equations exhibit discontinuities; and oscillations are commonplace. Standard theoretical techniques are no better than the empirical techniques. The problem, at the risk of oversimplification, is that the heat-transfer coefficient has a strong and complex temperature dependence unlike an ordinary gas (fig. 9).

The early experiments of Schmidt, Eckert, and Grigull (ref. 6) found free and natural convection in the vicinity of the critical point to exhibit a sharp increase in heat-transfer coefficient. On the other hand, Powell (ref. 54) reported a sharp minimum in heat-transfer coefficient in the T^* region for forced convection flow of liquid oxygen
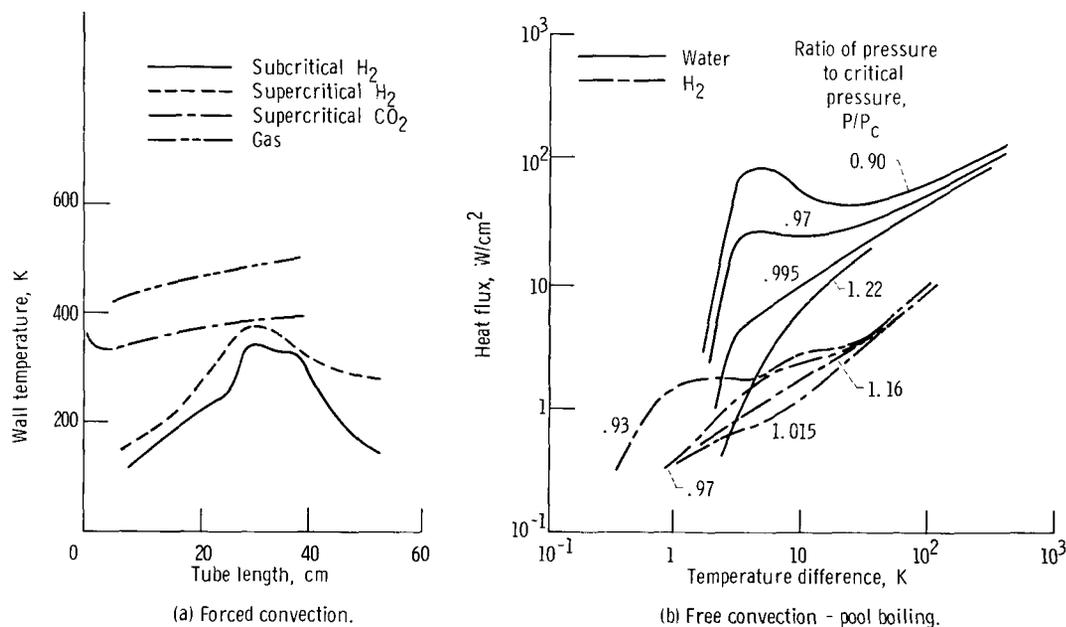
Figure 9. – Comparison between subcritical and supercritical heat-transfer behavior in forced and free convection
(refs. 41, 51, 59, 62, and 63).

and nitrogen. Since then, many other investigators have found similar "peaks" in the axial wall temperature profile (refs. 42, 55 to 57). In direct opposition, there are several researchers (refs. 58 to 61) who have reported a maximum heat-transfer coefficient (fig. 9(a)). The forced convection results of figure 9(a) are for hydrogen (ref. 42) and carbon-dioxide (ref. 59), while figure 9(b) represents pool heat transfer for hydrogen (ref. 62) and water (ref. 63). The similarities in wall temperature profiles for sub- and supercritical hydrogen data are also shown.

There are two associated results which may shed some light on this problem and which bear further investigation. First, both Shitsman (ref. 56) and Yamagata, et al. (ref. 57) showed heat-transfer coefficients, when plotted against bulk enthalpy, to be a minimum near the critical enthalpy and also reported pressure oscillations in the same region. Second, all the reports of a maximum in heat-transfer coefficient came from experiments (refs. 58, 60, 61, and 64 to 66) in which the temperature difference between the wall and the bulk fluid was small when compared to experiments in which a minimum occurred (refs. 56, 57, 67, and 68).

Hsu (ref. 69) suggested that the two results can be thought of qualitatively in boiling terms. When the temperature difference is small, it can be likened to nucleate boiling, a region of very good heat transfer, thus the maximum. When the temperature difference is large, it can be compared to film boiling, a region of poor heat transfer, thus the minimum. In support of this line of thinking, examine Hauptmann's data (ref. 70)
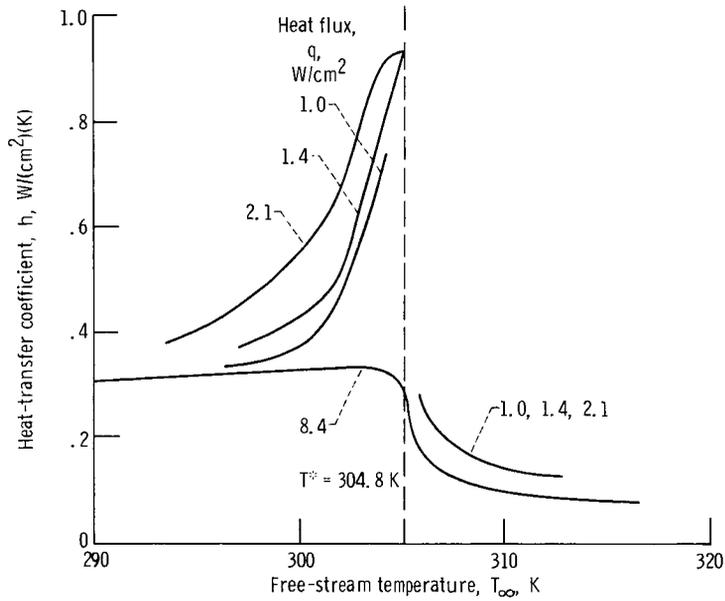
20

Figure 10. - Effect of free-stream temperature and wall heat flux on near-critical heat-transfer coefficient for carbon dioxide. Ratio of pressure to critical pressure, 1.025; free-stream velocity, 0.45 meter per second. (Data taken from ref. 70.)
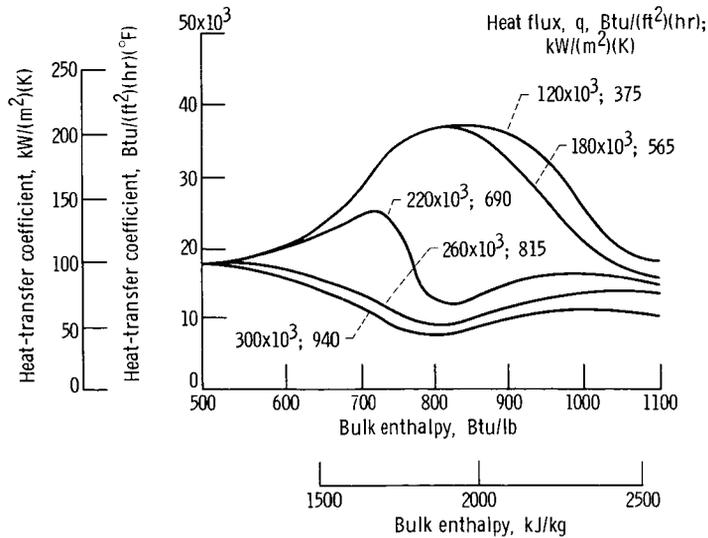

Figure 11. - Variation of heat-transfer coefficient with heat flux in critical region exhibiting both a maximum and a minimum. Mass flow rate, 700 kilograms per square meter per second. (From ref. 74.)
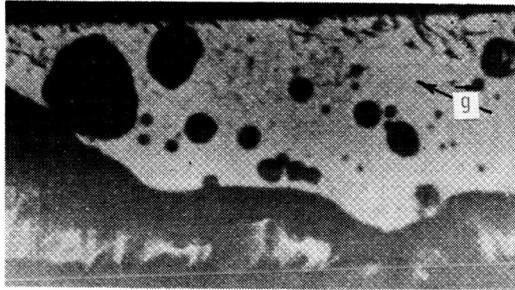
shown in figure 10. The small-temperature-difference data (i. e. , usually small heat flux q) exhibit a clear maximum, while the large-temperature-difference data (q = 8.4 W/cm^2) show, if anything, a minimum. A similar trend was found by Styrikovich, et al. (refs. 71 and 72) and is shown in figure 11. Wood (ref. 66) showed the heat-transfer coefficient to be a maximum near the critical point when plotted as a function of bulk temperature, and Kahn (ref. 73) showed the maximum to be a function of wall temperature. Shiralkar and Griffith (ref. 74) have found the heat-transfer coefficient to be strongly dependent on heat flux when wall temperatures are above T^* and bulk temperatures below T^*.

Pressure oscillations are a natural phenomenon of this regime and at times can be quite large, 0.3 P_{test} or 400 psi (27.2 atm) in nitrogen tetroxide as reported by McCarthy, et al. (ref. 75). Hines and Wolf (ref. 76) reported pressure oscillations of sufficient amplitude to damage their heated tubes.

Pressure drops are large and are primarily due to momentum changes (ref. 41). Friction losses become increasingly important as the heat-transfer process moves away from the near-critical regime.

The similarities in heat transfer, pressure drop, wall temperature profiles, and pressure oscillations between subcritical and the near-critical regimes is remarkable. In the early phases of the hydrogen work, the sounds of two-phase flow and supercritical flow were recorded (ref. 77). The sounds were similar, but supercritical sounds were not as "noisy." Goldman (ref. 78) has noted the same phenomenon. Researchers in this area (refs. 71, 79, and 80) often think of the fluid as pseudo-two-phase. Some of the strongest evidence in support of a pseudo-two-phase fluid comes from figure 6, from visual studies (refs. 62, and 81 to 83), and from heat-flux-against-temperature plots such as figure 9 (refs. 62, 63, and 83). Griffith and Sabersky (ref. 81) and Knapp and Sabersky (ref. 82) found the heated globules to be easily taken for bubbles. The film supplement to the work of Graham, et al. (ref. 62) gives the viewer a statistical feel for the nature of these similarities, as opposed to the instantaneous picture provided by the published photographs (e.g., ref. 82). Cumo, et al. (ref. 84) have documented the the change in fluid structure for Freon from atmospheric to the near-critical region as shown in figure 12. Nishikawa and Miyabe (ref. 83) published a set of photographs for the nucleate-film-boiling cycle and a comparative set at the reduced pressure of P/P_c = 1.065. The similarities at the film-boiling heat fluxes are particularly striking. The heat-flux-against-temperature-difference plots cited above, particularly those of Holt and Grosh (ref. 63), show the heat-transfer coefficient to be a function of heat flux - a phenomenon not found in normal gas heat transfer, but a trademark of boiling. One possible explanation of the unusual wall temperature profiles discussed earlier is a "boiling" model.
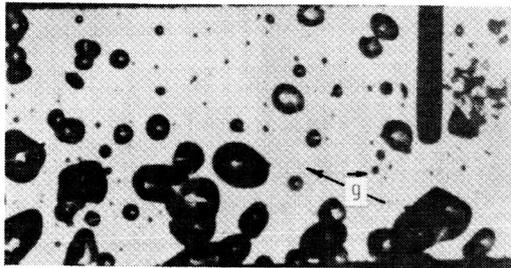
The strongest argument against such a pseudo-two-phase fluid is thermodynamic; a supercritical fluid in equilibrium is clearly single phase. Pseudo-two-phase-fluid

Reduced pressure, P/P_c: 0.17   0.79

Temperature, t, °C: 56   135

Mass flow per unit area, G, g/cm²: 114   111.5

0.30	0.93
72	140
104	74.3
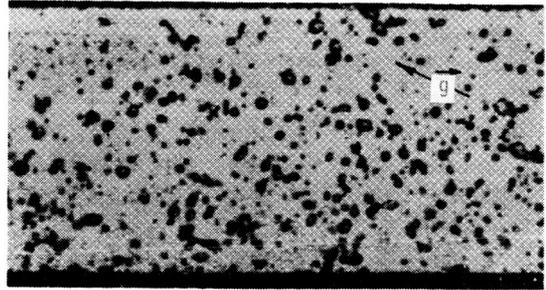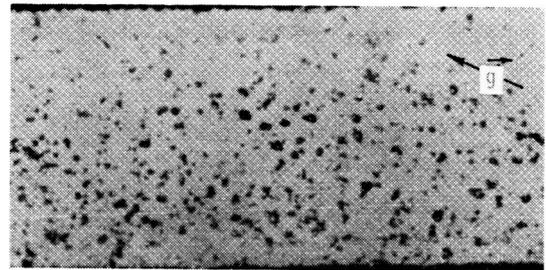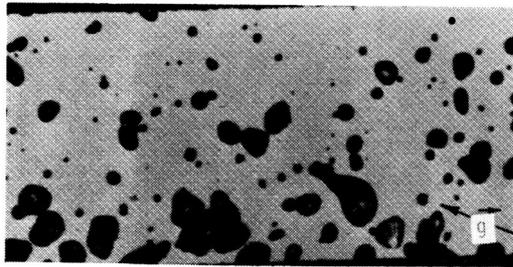
0.47	1
102	142
101.5	92
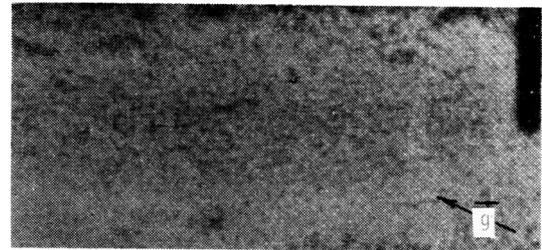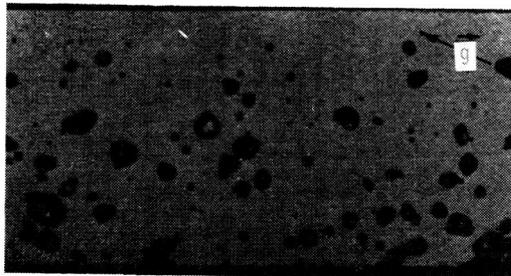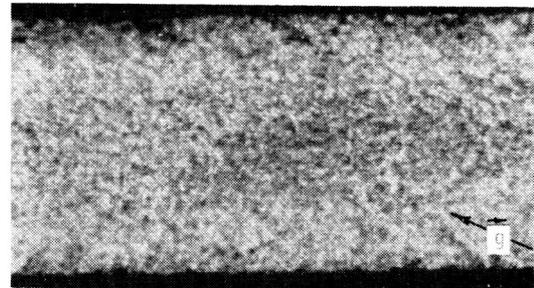
0.62	1.12
122	141
111.5	74.3

C-70-2101

Figure 12. – Heat transfer to Freon-114 at various pressures. (From ref. 84).

advocates recognize this, and most, such as Miyabe (ref. 83) and others, claim that it is a nonequilibrium situation. Experimentally it is very interesting that the single-phase proponents use the same visual evidence presented by the two-phase advocates. Hauptmann (ref. 70) uses his own very dramatic photographs and reexamines the other visual experiments (refs. 70 and 81), and concludes that all of the unusual results can be explained in single-phase terms. A careful examination of all the available photographs (refs. 62, 70, and 81 to 83) reveals as many nonsimilarities to boiling as there are similarities. Really, the analyst has his choice because a strong case can be made for either model; however, it is clear that there are no sharp discontinuities in the heat-transfer data (refs. 67 and 63). Any analytic model (pseudo-two-phase or single-phase) should work throughout region IV (fig. 8) and provide smooth transition from liquid to gas if properly formulated.

The heat-transfer results change from apparatus to apparatus. For example, figure 13 illustrates changes in heat transfer for hydrogen as tube diameter is changed. At the larger diameter, the L/d effects are large and not accounted for by the pseudo-fluid or single-phase models. Thus the results appear to be system-dependent, so geometry effects must also be carefully assessed.
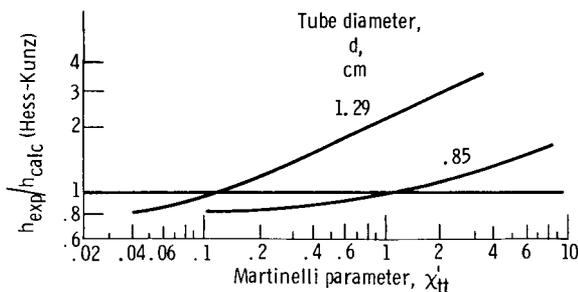
(a) Hess and Kunz correlation dependence on pseudo-Martinelli parameter and diameter (ref. 41).
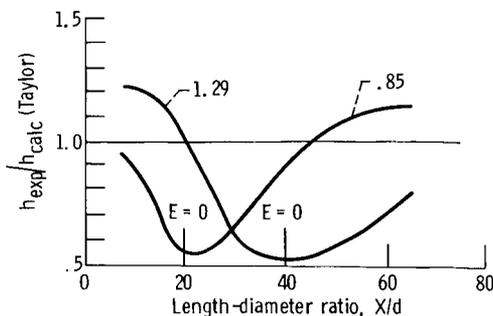
(b) Taylor equation behavior for two different tube diameters.

Figure 13. - Some geometry effects in near-critical-fluid heat transfer.

In summary we can say

(1) Some characteristics of the near-critical region are

    (a) Nonlinearities in heat flux against temperature difference

    (b) Wall temperature excursions (spikes)

    (c) Similarities to the two-phase regime

    (d) Oscillations

    (e) Large momentum pressure drops

    (f) System-dependent results

    (g) Failure of conventional correlations

(2) Modeling should be required to work throughout region IV, and should exhibit a smooth transition to the adjacent regions shown in figure 8.

Heat Transfer in Free Convection Systems

The free convection pool studies discussed in this section deal primarily with heat transfer from small test sections, such as wires, filaments, and plates. In a subsequent section, the heat transfer from natural convection loops will be considered.

The effect of the wide variations of properties appears to have a more direct influence in the pool-heat-transfer case. This is probably true because in this situation temperature differences are usually small. Pool results almost universally show enhancement in heat transfer near the critical point. Some typical experimental data where enhancement occurred are those of Dubrovina and Skripov (ref. 85) shown in figure 14.
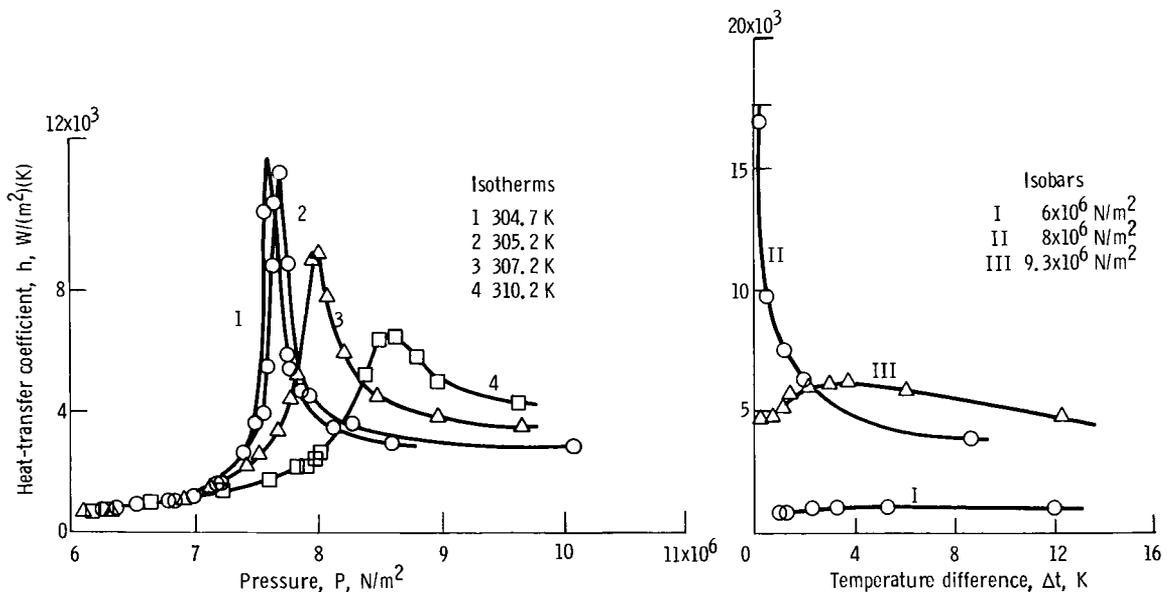

Figure 14. – Free convection heat transfer for carbon dioxide. Data show heat-transfer-coefficient behavior as the properties near the critical point, when temperature differences are very small. (From ref. 85).

TABLE II. - FREE CONVECTION - POOLS

Investigator	Date of work	Reference	Fluid	Geometry	Range of conditions		Constants
					Ratio of pressure to critical pressure, P/P_c	Ratio of temperature to critical temperature, T/T_c	
Doughty and Drake	1956	186	Freon-12 (CCl_2F_2)	Horizontal wire	0.28 to 1.7	0.77 to 1.04	$n = 1/3$ $C = 0.14$
Bonilla and Sigel	1960	187	n-pentane (C_5H_{12})	Horizontal plate	0.72 to 1.5	0.65 to 0.74 (fluid) 0.71 to 1.06 (surface)	$C = 0.172$ $n = 1/3$ $\beta_1 \Delta T = \ln(\rho_b/\rho_w)$
Griffith and Sabersky	1960	81	Freon-114A $(C_2Cl_2F_4)$	Horizontal wire	0.42 to 1.15	0.725 to 1.08	---------------
Skripov and Potashev	1962	188	CO_2	Vertical wire	0.82 to 1.25	1.00 to 1.02	---------------
Brodowicz and Bialokoz	1963	189	Freon-12 (CCl_2F_2)	Vertical plate	1	0.98 to 1.07	---------------
Holt and Grosh	1963	63	H_2O	Horizontal wire and vertical ribbon	1.5×10^{-4} to 1.25	0.75 to 1.0 (fluid) 0.75 to 2.0 (surface)	---------------
Fritsch and Grosh	1963	190, 191	H_2O	Vertical ribbon	1.03 to 1.06	1.0036 to 1.0086	---------------
Dubrovina and Skripov	1964	85	CO_2	Horizontal wire, horizontal and vertical ribbon	0.99 to 1.3	1.00 to 1.03	---------------
Knapp and Sabersky	1965	82	CO_2	Horizontal and vertical wire	1.03 to 1.40	0.93 to 1.09	---------------
Nishikawa and Miyabe	1965	83	CO_2	Horizontal wire	1.00 to 1.33	0.98 to 1.63	Pseudocritical properties analysis
Graham, Hendricks, and Ehlers	1965	62	H_2	Horizontal ribbon	0.32 to 1.38	0.76 to 1.19	$0.25 \le n \le 0.35$
Larson and Schoenhals	1966	192	H_2O	Vertical ribbon	1.01 to 1.03	0.98 to 1.04	$a = 1/3$ $b = 0.247$ $c = 0.137$ $x = 0.5$ Eq. (15)
Goldstein and Aung	1967	86	CO_2	Horizontal wire	1.03 to 1.21	0.94 to 1.09	---------------
Daniels and Bramall	1965	193	CO_2	Horizontal Monel wire	0.79 to 1.16	0.86 to 1.03	---------------

The enhancement of the heat-transfer coefficient is very pronounced but also limited to a very small temperature range. Also the enhancement peaks somewhat away from the critical point and in the region of the transposed critical temperature.

Unlike a forced convection system, the free convection system has no constraining boundaries. Consequently, it is able to respond to favorable property variations with enhanced heat transfer.

Although boiling-like behavior has been reported for pools (refs. 63 and 81), the onset of this behavior was not characterized by a marked change in the heat-transfer coefficient, as is the case with the onset of nucleate boiling. This can be seen in the supercritical curves of figure 9. Although the mechanisms for nucleate boiling and near-critical heat transfer may be similar, some aspects of the energy transport must be different.

Some interesting near-critical free convection experiments are those of references 82, 86, and 87 using a small-diameter horizontal wire. Knapp and Sabersky (ref. 82) were the first to photograph an oscillation back and forth between laminar and turbulent flow while heating near-critical carbon dioxide. Their data indicated a sharp increase in heat transfer in going from the all-laminar to the all-turbulent region; however, the transition through the oscillating region appeared to be smooth. The authors indicate that this is probably because the data were average data, and that they suspect an oscillation in wire temperature to go with the laminar-turbulent oscillation. Goldstein and Aung (ref. 86) reported similar oscillations but no sharp increase in heat transfer. The phenomenon remains unexplained at present; however, such oscillations may well be fundamental to our understanding of the oscillations noted in forced convection and natural convection loops.

Recently, Hahne (ref. 88) conducted the classic free convection experiment between two horizontal plates, using supercritical carbon dioxide. He found "spindle-like" structures, rather than the classic Benard cells.

The pool experiments in the near-critical region are summarized in table II. Most of the data analyses of the papers shown in table II employ rather conventional dimensionless groups. In some cases, there have been modifications, primarily to account for the variable properties in the boundary region (refs. 89 to 91). There appears to be general agreement that somewhat away from the critical and transposed critical points the conventional correlations will hold for all fluids and for all systems, as discussed in the section HEAT-TRANSFER REGIONS. Thus, away from the critical point, McAdams basic equation (ref. 48)

$$(Nu)_f = C(Ra)^n \qquad (14)$$

should work. Closer to the critical point, modifications of the following basic form are employed:

$$(Nu)_x = C(Gr)_x^a(Pr)_x^b \left(\frac{T_\infty}{T_w - T_\infty}\right)^c \qquad (15)$$

Specific details are listed in table II. Very close to the critical point, Simon and Eckert (ref. 92) recommend

$$\frac{q\sqrt{\dfrac{|T - T_c|}{T_c}}}{\rho_c \lambda_w \left(\dfrac{\partial T}{\partial \rho}\right)_P} = 3.25 \times 10^{-9} \frac{(Ra)_w}{\sqrt{(Pr)_w}} \qquad (16)$$

In summary,

(1) Pool results almost universally show an enhancement in heat transfer near the critical point. In all cases, the temperature differences are small and the enhancement occurs over a limited temperature range and peaks somewhat away from the critical point. Large temperature differences diminish the peak.

(2) Free convection systems have no constraining boundaries and consequently respond favorably to property variations.

(3) Boiling-like behavior in near-critical pools is not accompained by the marked increase in heat-transfer coefficient of nucleate boiling.

(4) Most researchers employed conventional techniques away from the critical point. However, close to the critical point, modifications such as equations (15) and (16) are employed (see table II).

(5) Laminar-to-turbulent oscillations have been observed, but the origin of this phenomenon has not been explained. These oscillations may well determine the character of near-critical oscillations found in natural and forced convection systems.

Heat Transfer in Loops – Natural Convection Systems

Historically, there has been considerable interest in the use of a natural convection loop or column (fig. 15). Here a fluid in the supercritical region can operate at high heat flux.

Experiments and analyses in natural convection loops begin with the work of Schmidt (refs. 6, and 93 to 95). As in pools, the results of loop experiments are universally an enhancement of heat transfer near the critical point when compared to noncritical fluids under similar heat-transfer conditions. And as in forced convection systems,
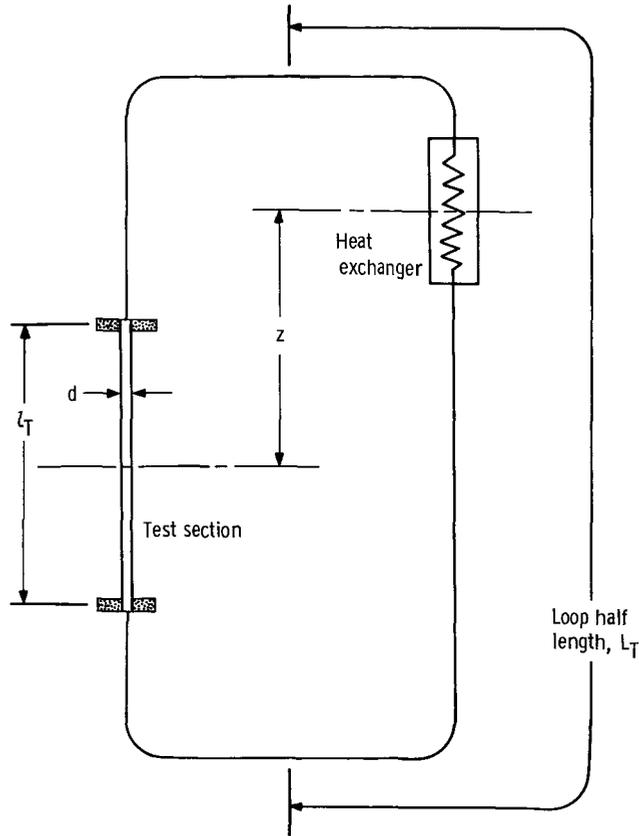
Figure 15. – Schematic of a typical natural convection loop.

oscillations appear to be dependent on the proximity to the critical point, as will be discussed in a later section. The laminar-to-turbulent-flow oscillations noted in near-critical pools could be the origin of the oscillations noted in natural convection loops.

Further evidence of similarities to forced convection are the body force effects at low flow (discussed under geometry effects) and heat transfer at low $\Delta T = T_w - T_b$.

In an effort to correlate near-critical data, Holman and Boggs (ref. 96) rearranged Schmidt's basic loop equations to the form

$$Nu = 16(Re)^2 (Pr)(Gr)^{-1} \left(\frac{l_T}{L_T}\right)\left(\frac{d}{\xi}\right) \quad \text{(laminar)} \qquad (17)$$

$$Nu = 0.079(Re)^{11/4}(Pr)(Gr)^{-1} \left(\frac{l_T}{L_T}\right)\left(\frac{d}{\xi}\right) \quad \text{(turbulent)} \qquad (18)$$

To test the geometry effects, Tanger, et al. (ref. 97) compared sulfur hexafluoride
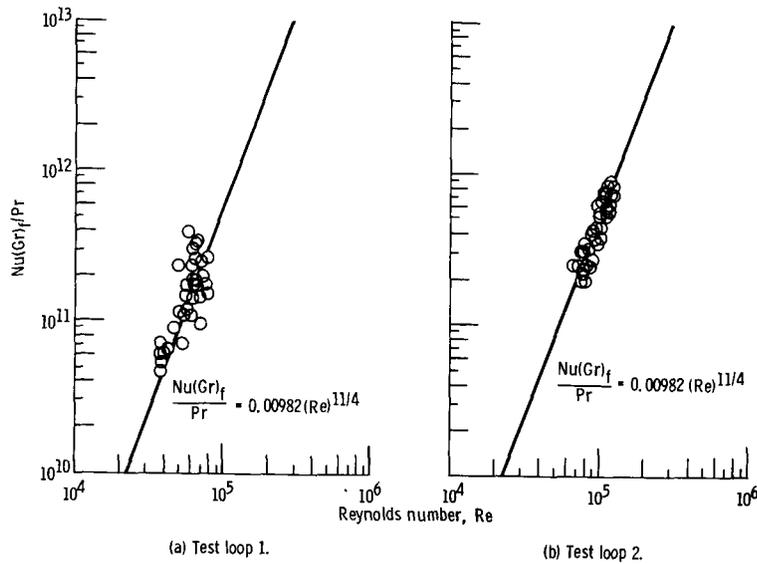
Figure 16. - Correlation of near-critical sulfur hexafluoride data in natural convection loops of different geometries. (From ref. 97.)

data obtained in two different loops. For a fixed l_T and d, the geometry factors of equations (17) and (18) of loop 1 were approximately 1.8 those of loop 2. They found no effect due to geometry varations. For the critical region, they recommend

$$\frac{Nu(Gr)_f}{Pr} = 0.00982(Re)^{11/4} \tag{19}$$

The results are shown in figure 16. Merlini (ref. 98) found a very strong influence of the transposed critical temperature on both heat transfer and oscillations. He used the experimentally determined film-to-centerline fluid temperature ratio $T_x/T_{\mathcal{L}}$ to correlate his data

$$Nu = Const(Re)^{0.65}(Pr)^{0.15}\left(\frac{T_x}{T_{\mathcal{L}}}\right)^{-5.27} \tag{19a}$$

where

$$Const = \begin{cases} 0.287 & \dfrac{T_x}{T_{\mathcal{L}}} > 1.2 \\[2em] 0.196 & \dfrac{T_x}{T_{\mathcal{L}}} < 1.2 \end{cases}$$

30

TABLE III. - NATURAL CONVECTION - LOOPS

Investigator	Date of work	Refer- ence	Fluid	Geometry	Range of conditions	
					Ratio of pressure to critical pressure, P/P_c	Ratio of temperature to critical temperature, T/T_c
Schmidt, Eckert, and Grigull	1939	6	Ammonia (NH_3)	Loop: 0.59 in. i.d., 7.4 ft long	0.52 to 1.29	0.6 to 1.25
Schmidt	1951	93	H_2O	Turbine blades (hollow core)	1	0.77 to 1.07
Van Putte and Grosh	1960	194	H_2O	Test section: 5 ft long, 0.245 in. i.d.	0.03 to 1.25	Up to 1.12
Merlini	1968	98	H_2O	Loop: 0.742 in. i.d., 42 ft long	1.06 to 1.24	0.735 to 1.016
Holman and Boggs	1966	96	Freon-12 (CCl_2F_2)	Loop: 0.43 in. i.d. 49 ft long	0.84 to 1.5	0.88 to 1.39
Harden and Boggs	1964	155	Freon-114 $(C_2Cl_2F_4)$	Loop: 0.93 in. i.d., 49 ft long	-----------	-------------
Cornelius and Parker	1965	151	Freon-114 $(C_2Cl_2F_4)$	Loop: 0.93 in. i.d., 49 ft long	1.0 to 1.1	0.86 to 1.0
Tanger, Lytle, and Vachon	1968	97	Sulfur hexafluoride (SF_6)	2 loops: 43 in. i.d., 28 and 38 ft long, varied vertical distribution between condition and heater	0.98 to 1.64	0.995 to 1.14
Hahne	1965	195	CO_2	Closed inclined tube	Constant volume and temper- ature experiment	

Because of this equation's extreme dependence on $T_x/T_{\mathfrak{e}}$, the reader should become familiar with reference 98 and exercise caution where applying equation (19a). The experiments in natural convection loops are summarized in table III.

The results obtained in free convection pools bear many similarities to the results for natural convection loops; however, there are also many similarities between loops and forced convection systems.

In summary,

(1) In free convection pools and natural convection loops, close proximity of the fluid to the critical point appears to enhance heat transfer. This is possibly the result of a free boundary system being able to respond to enhancing property variations when the temperature differences are low. As will be shown, forced convection systems at low temperature differences exhibit similar trends.

(2) Reasonable success has been achieved in correlating the data of both the pools and natural convection loops by variable property modifications to the standard equations for the given configuration.

(3) The pool experiments have produced considerable support for a pseudo-two-phase modeling of a near-critical fluid. On the other hand, the success of single-phase correlations indicates either approach may be successful.

(4) To date no single correlation has been tested against all the available data.

(5) Since these experiments operate very close to the critical point, there is a continuning need for improved property data and equations of state.

(6) System oscillations which are commonplace in a natural convection loop near the critical point are similar to those observed in forced convection systems.

Heat Transfer in Forced Convection Systems

The experimental work in near-critical forced convection can be broken into two major categories. First are the conventional heated-tube experiments which have been used so successfully in determining Nusselt correlations for gases. In the second category are experiments which examine one or two details of the heat-transfer process in order to explain the mechanism of near-critical heat transfer.

Heated-tube experiments. - In the past 17 years, over 30 experiments in forced convection heat transfer to supercritical fluids, which fall into the broad classification known as heated-tube experiments, have been conducted. All these experiments were very similar in design, operating procedure, measurements, and to some extent, results. These experiments can be surveyed as a group, pointing out specifics where necessary. The range of these experiments, which by now is quite extensive, is summarized in table IV. The most popular fluids have been water, hydrogen, and carbon

TABLE IV. - FORCED CONVECTION - HEATED-TUBE EXPERIMENTS

Investigator	Date of work	Reference	Fluid	Range of conditions							Correlation attempts	
				Ratio of pressure to critical pressure, P/P_c	Ratio of bulk to critical temperature, T_b/T_c	Ratio of wall to critical temperature, T_w/T_c	Heat flux, q, W/cm^2	Mass flow per unit area, G, g/cm^2-sec	Characteristic length (diameter) d, cm	Length-diameter ratio, L/d	Equation	Constants
Monroe, Bristow, and Newell	1952	80	O_2	1.03 to 2.74	0.99 to 1.29	1.07 to 1.60	0.29 to 12.8	2.72 to 71.5	12.7	75 to 220	None	-------------
Chalfant *Randall* Goldman	1954 1956 1961	196 197 198	H_2O	1.56	0.74 to 1.25	0.74 to 1.60	32 to 940	210 to 550	1.27 to 1.90	10 to 120	None	-------------
Dean and Thompson	1956	79	N_2	0.61 to 1.22	0.64 to 0.66	0.8 to 9.0	65 to 810	-----------	4.75	Average	None	-------------
Bringer and Smith	1957	100	CO_2	1.12	0.97 to 1.06	1.02 to 1.12	3.2 to 32	54 to 220	4.57	0 to 133	(15)	$C = 0.0266$, $a = 0.77$, $(Pr)_x^b = (Pr)_w^{0.55}$, $p = 0$, $x = f[(T^* - T_b)/(T_w - T_b)]$
Powell	1957	54	O_2	1.20 to 1.44	0.63 to 3.6	2.5 to 7.4	190 to 800	300 to 2740	4.93	31 to 371	Mixing length	-------------
Miropolskii, Picus, and Shitsman Miropolskii and Shitsman	1966 1957	105 102	H_2O	0.018 to 1.29	0.43 to 1.07	-----------	29 to 2320	17 to 3000	2.9 to 8.2	10 to 40	(17)	-------------
Dickinson and Welch	1958	64	H_2O	1.09, 1.41	0.58 to 1.25	0.65 to 1.33	870 to 1820	220 to 340	7.62	25 to 180	(15)	$C = 0.023$, $a = 0.8$, $b = 0.4$, $p = 0$, $x = 0$
Morra and Barger DelBene and Barger	1958 1959	199 200	CCl_2F_2	0.98 to 1.30	0.97 to 1.22	0.98 to 1.72	0.55 to 10.7	21 to 71	8.90	0 to 131	None	-------------
Schmidt	1951	67	H_2O	0.78 to 1.37	0.73 to 1.25	0.77 to 1.55	29 to 82	70, 120	5.0, 8.0	-----------	None	-------------
Koppel and Smith	1961	59	CO_2	1.000 to 1.03	0.96 to 1.06	1.10 to 2.10	6.3 to 63	26 to 135	4.93	2.5 to 93	None	-------------
Petukhov, Krasnoschekov, and Protopopov	1961	60	CO_2	1.20 to 1.46	0.98 to 1.15	1.01 to 1.16	3.4 to 12.0	68	6.70	5 to 97	(19)	$a = -0.11$, $b = 0.35$, $c = 0$, $d = 0.35$ ($Nu = Nu(Re, Pr, f)$)
Thompson and Geery	1961	68	$p-H_2$	3.58 to 7.10	0.92 to 3.93	2.0 to 26.6	18 to 1300	-----------	4.93	20.6, 41.2	(15)	See ref. for constant
Szetela	1962	143	$p-H_2$	-----------	-----------	-----------	-----------	-----------	6.58 to 11.4	1 to 34	None	-------------
Shitsman	1963	56	H_2O	1.05 to 1.15	0.85 to 1.01	0.91 to 1.35	≤ 115	30 to 150	8.0	10 to 186	(17)	-------------
Domin	1963	58	H_2O	1.01 to 1.19	≤ 1.12	≤ 1.53	1.15 to 115	≤ 516	2.0, 4.0	Average	(17)	-------------
Wood	1963	66	CO_2	1.004, 1.03	0.94 to 1.01	0.99 to 1.08	3.2 to 20.5	144 to 226	22.9	30.8	Mixing length	-------------
Krasnoshchekov and Protopopov Krasnoschekov, Protopov, Feng, and Kuraeva	1964 1966	106 201	CO_2	1.06, 1.33	0.96 to 1.26	0.97 to 2.6	4.6 to 260	-----------	4.08	1 to 51	(19)	$a = 0$, $b = 0$, $c = 0.3$, $d = f(T_b, T_w, T^*)$ ($Nu = Nu(Re, Pr, f)$)
Finn	1964	108	C_3H_8	1.13	0.84 to 1.07	0.96 to 1.43	3.15 to 38	53 to 173	7.65	3.5 to 67	(19)	$a = -0.02$, $b = 0.20$, $c = -0.27$, $d = 0.54$
Miller, Seader, and Trebes	1965	55	$p-H_2$	2.13 to 13.3	0.85 to 3.09	≤ 16	223 to 3910	250 to 1180	5.34	2.5 to 55	(21)	$C = 0.0204$, $x = 0.4$, $a = 0.00983$
Holman, Rea, and Howard	1965	202	CCl_2F_2	0.90 to 1.27	0.95 to 1.08	1.00 to 1.30	0.47 to 27	17 to 44	12.7×44.4 annulus	-----------	(20)	See ref. for constants
Hendricks, Simoneau, and Friedman	1965	203	$p-H_2$	5.30 to 13.3	1.00 to 3.36	2.5 to 20.0	58.5 to 1630	28 to 840	5.35 to 11.1	3.4 to 78.2	(15)	$C = 0.021$, $a = 0.8$, $b = 0.4$, $x = 0.5$, $p = 0$
Swenson, Carver, and Kakarala	1965	61	H_2O	1.03 to 1.88	0.54 to 1.31	0.57 to 1.42	20 to 182	54 to 218	9.43	20.2 to 182	(19)	Slightly different form (see ref.)

TABLE IV. - Concluded. FORCED CONVECTION - HEATED-TUBE EXPERIMENTS

Investigator	Date of work	Refer- ence	Fluid	Range of conditions							Correlation attempts	
				Ratio of pressure to critical pressure, P/P_c	Ratio of bulk to critical temperature, T_b/T_c	Ratio of wall to critical temperature, T_w/T_c	Heat flux, q, W/cm^2	Mass flow per unit area, G, g/cm^2-sec	Character- istic length (diameter) d, cm	Length- diameter ratio, L/d	Equa- tion	Constants
Bishop, Krambeck, and Sandberg	1965	204	H_2O	0.75 to 0.975	0.97 to 1.24	1.02 to 1.41	23 to 256	66 to 330	2.54, 5.08	30 to 385	(15)	C 0.0073, a 0.886, b 0.61, x 0.5, p 0, plus L/d term
Hendricks, Graham, Hsu, and Friedman	1966	41	$p-H_2$	0.43 to 4.37	0.75 to 8.38	2.0 to 15.0	33 to 540	14 to 510	4.75 to 12.8	5 to 114	(22)	--------------------
Tanaka, Nishiwaki, and Hirata	1967	65	CO_2	1.06	0.987 to 1.02 .997 to 1.03	------------	[a]1.43 to 5.20 [b]1.43 to 8.14	50 to 100	10.0	5 to 95	Mixing length	--------------------
Yamagata, Nishikawa, Hasegawa, and Fujii	1967	57	H_2O	1.15	0.607 to 1.25	0.915 to 1.50	11.6 to 93	32.3 to 108	10.0	10 to 190	(19)	Constant $f[(T^* - T_b)/(T_w - T_b)]$ (see ref.)
Schnurr	1969	101	CO_2	1.003 to 1.03	0.97 to 1.04	1.07 to 1.39	25 to 189	------------	2.64	1 to 75	(15)	C 0.0266, a 0.77, $(Pr)_x^b = (Pr)_w^{0.55}$, p = 0, $x = f[(T^* - T_b)/(T_w - T_b)]$ (Nu Nu(Re, Pr, f))
Armand, Tarasova, and Konkov	1959	205	H_2O	1.04 to 1.19	------------	------------	18.7 to 73.5	45 to 65	6.0, 8.0	3.1 to 37	(17)	C 0.0215
Shitsman	1962	206	H_2O	1.03 to 1.19	0.89 to 1.03	0.82 to 1.01	[b]29 to 580	10 to 250	8.0	4 to 18	(19)	a -0.25, b 0.33, c 0, d 0.35 (Nu Nu(Re, Pr, f))
Krasnoschekov and Protopopov	1959	145	CO_2	1.23 to 1.37	------------	------------	------------	------------	6.70	5 to 95	(19)	For regions see ref.
Glickstein and Whitesides	1966	207	CH_4	0.3 to 1.2	0.3 to 1.8	------------	to 374	89 to 362	8.5	99	(22)	Not x_{tt} dependent
Beech[c]	1967	208	Kerosene	0.83 to 3.0	0.43 to 0.46	0.44 to 1.17	to 250	250 to 265	6.0	51.5	-----	$St(Pr)^{0.6}$ 0.0034 Tube in a rectangular passage
Kafengauz	1969	153	Diisopropyl cyclohexane	1.5 to 2.5	------------	------------	------------	------------	0.8 to 2.3	13 to 38	None	--------------------
Von Berg, Williamson, and Edeskuty	1969	209	N_2	0.81 to 1.22	0.70 to 1.23	------------	1.9 to 7.5	1.1 to 6.8	34.8	131	(10)	--------------------
Hay	1969	210	He	1.7 to 10.2	0.80 to 1.50	0.85 to 1.60	------------	3.9 to 22	0.25	600	None	--------------------
Povarnin and Maikina	1969	211	Various hydro- carbons	2 to 4	------------	------------	35	400 to 3200	1 to 3	100	(20)	--------------------
Touba and McFadden	1966	212	H_2O	1.006 to 1.06	0.916 to 1.01	0.926 to 1.11	55.5 to 165	115 to 525	0.622 and 0.94	212 and 151	-----	$\left[\dfrac{q}{(H_w - H_b)G}\right](Re_b)^{0.2}$ 0.0068 $\cdot \exp\left[2.19\left(\dfrac{H_b}{H^*} - 0.801\right)\right]$

[a]Heating.
[b]Cooling.
[c]Also in an unpublished English Ministry of Technology Report by Beech and Ziebland entitled "Heat Transfer to Kerosine at Supercritical and Subcritical Pressures."

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dioxide; and the flow is normally vertically upward. The emphasis in many of these ex-
periments was on data correlation.

The correlation attempts can be treated in a general manner as to form. Early work
centered on reference temperature modifications to the basic Dittus-Boelter equation:

$$(Nu)_x = C(Re)_x^a (Pr)_x^b \left(\frac{T_w}{T_b}\right)^p \tag{20}$$

where x means that the fluid properties are evaluated at $T_x = T_b + x(T_w - T_b)$. Eckert
(ref. 99) suggested that x may be a function of a dimensionless temperature frequently
called the Eckert parameter

$$x = f\left(\frac{T^* - T_b}{T_w - T_b}\right) \tag{21}$$

Bringer and Smith (ref. 100) and Schnurr (ref. 101) have plotted these functions, as
shown in figure 17. While this treatment handles quite a bit of data, it has never been
generalized to other data and no analysis is available to predict the function.
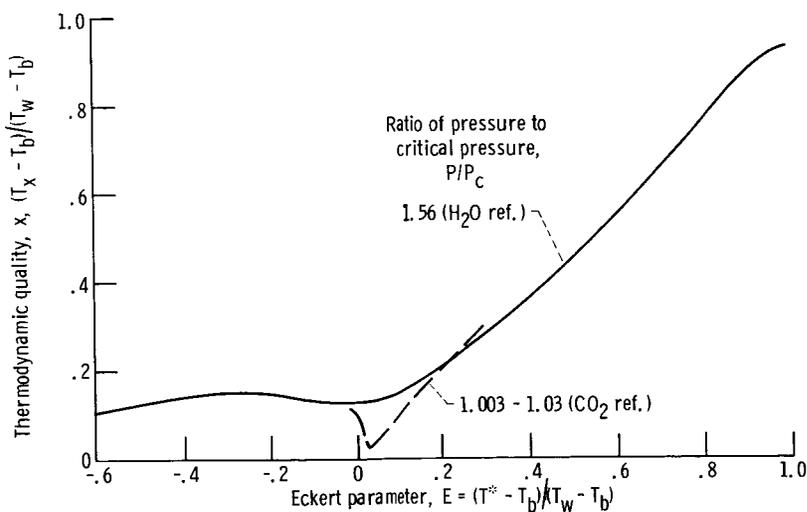
Figure 17. - Effect of relative proximity to the critical point on Eckert reference tem-
perature (refs. 59, 101, and 135).

Another early correlation directed specifically at heat transfer near the critical point was that of Miropolskii and Shitsman (ref. 102); using water experiments they proposed

$$(Nu)_b = 0.023(Re)_b^{0.8}(Pr)_{min}^{0.4} \tag{22}$$

where $(Pr)_{min}$ is the minimum Prandtl number, defined as

$$(Pr)_{min} = \begin{cases} (Pr)_b & (Pr)_b < (Pr)_w \\ (Pr)_w & (Pr)_w < (Pr)_b \end{cases} \tag{22a}$$

This amazingly simple modification to the Dittus-Boelter equation produced some remarkable results. Miropolskii and Shitsman (ref. 103) made a plot (redrawn in fig. 18) for water at 230 atmospheres (P_c = 218.2 atm) using equation (22). Figure 18 shows a sharp peak in heat-transfer coefficient at $T_b \rightarrow T^*$ and the peak decreases with increased heat flux until, with an order of magnitude increase in q, there is practically no peak. Compare this to the data from Hauptmann's experiment (ref. 70) for carbon dioxide flowing over a flat plate, shown in figure 10. The qualitative similarities between these data and the Miropolskii and Shitsman calculations (fig. 18) are striking. In
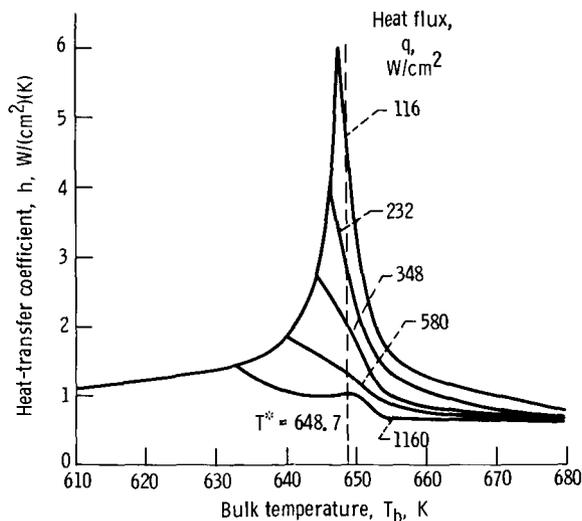
Figure 18. - Calculations of heat-transfer coefficient for water by Miropolsky and Shitsman correlation (eq. (22)). Ratio of pressure to critical pressure, 1.052; mass flow rate, 100 grams per square centimeter per second; tube diameter, 30 millimeters. (Data from ref. 103.)

Hauptmann's data, however, the heat-transfer coefficient first increased, then decreased with heat flux. The data also showed a marked transverse body-force effect which, of course, the correlation could not comprehend. Shitsman (ref. 104) successfully extended this correlation to include the water data of Dickinson and Welch (ref. 64), the oxygen data of Powell (ref. 54), and the carbon dioxide data of Bringer and Smith (ref. 100). Particularly interesting was the fact that the correlation comprehended both the maximum in heat-transfer coefficient reported by Dickinson and Welch and the minimum reported by Powell. Later, however, using water, Shitsman (refs. 103 and 105) also discovered experimentally the same temperature "spikes," shown typically in figure 11, that Powell (ref. 54) reported for oxygen. He called this a region of "impairment" to heat transfer and likened it to boiling crisis. He cautioned his readers that equation (22) would not correlate this region despite the fact that it had earlier handled Powell's similar conditions. The authors have tried this equation on the hydrogen data of Hendricks, et al. (ref. 41) with unsuccessful results.

Another correlation directed at the critical point is of the form

$$Nu = (Nu)_b \left(\frac{\eta_w}{\eta_b}\right)^a \left(\frac{\lambda_w}{\lambda_b}\right)^b \left(\frac{\rho_w}{\rho_b}\right)^c \left[\frac{\overline{C}_p}{(C_p)_b}\right]^d \tag{23}$$

where $(Nu)_b$ is the Dittus-Boelter value (eq. (10)) and $\overline{C}_p = (H_w - H_b)/(T_w - T_b)$. Versions of equation (23) have been used for carbon dioxide (refs. 60 and 106), for water (refs. 61 and 107) and for propane (ref. 108). The key characteristic would seem to be the integrated specific heat $\overline{C}_p$.

The concept of using not only integrated specific heat, but all physical properties on an integrated average basis was put forth by Brokaw (ref. 109) for a reacting N_2O_4 system. The properties would be expressed as

$$\overline{\varphi} = \frac{1}{T_w - T_b} \int_{T_b}^{T_w} \varphi(t)dt \tag{24}$$

where $\varphi(t)$ is any fluid property. This has a tendency to smooth out the sharp near-critical property changes, as shown in figure 19 for density. Since near-critical fluids can be thought of as dissociating, this approach could have merit. Furthermore, if the temperature profile is known, or a reasonable assumption for the profile is made, the integral average property becomes

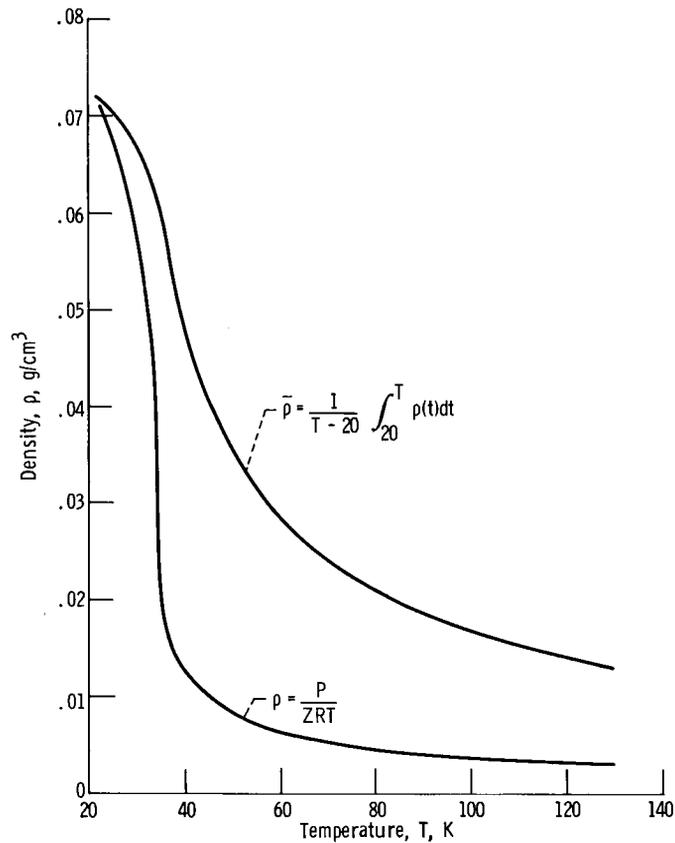$$\overline{\varphi}_1 = \frac{1}{r} \int_0^r \varphi[T(y)]dy \tag{24a}$$

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Figure 19. - Integral average properties as defined by Brokaw (ref. 109) in comparison to equilibrium properties, for parahydrogen.

Hess and Kunz (ref. 110) proposed a correlation of the form

$$(Nu)_x = C(Re)_x^{0.8}(Pr)_x^{0.4}\left(1 + a \frac{\nu_w}{\nu_b}\right) \tag{25}$$

This has worked reasonably well for hydrogen (ref. 55).

Most authors have been reluctant to propose "pseudoboiling" models for forced convection heat transfer. Hendricks, et al. (refs. 41 and 42) have suggested modification of two boiling concepts, the Martinelli parameter (ref. 111) and the Stermann parameter (sometimes called boiling number) (ref. 112), for use in the supercritical region:

$$(Nu)_f = (Nu)_{fm}f(\chi_{tt}', Sr) \tag{26}$$

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where

$$(\chi_{tt})' = \left(\frac{1 - x_2}{x_2}\right)^{0.9} \left(\frac{\eta_1}{\eta_{pg,f}}\right)^{0.1} \left(\frac{\rho_{pg,f}}{\rho_1}\right)^{0.5} \tag{26a}$$

and

$$Sr = \frac{q\ \Delta v}{u_b\ \Delta H} \tag{26b}$$

where the subscript 1 refers to the liquid or heavy species. While the functional relation has not been specified, these parameters have shown some success in grouping the data.

Wilson (ref. 113) used a somewhat similar concept:

$$\frac{1}{(Nu)_w} = a + bN_{sk} \tag{26c}$$

where

$$N_{sk} = \frac{Q - \dot{\omega}(H_l - H_{inlet})}{\dot{\omega}(H_g - H_l)} \tag{26d}$$

and

$$a = 1.033{\times}10^{-4}; \quad b = -1.708{\times}10^{-3} \qquad N_{sk} < -0.2$$

$$a = 7.868{\times}10^{-4}; \quad b = 1.613{\times}10^{-3} \qquad N_{sk} > -0.2$$

If an equation is listed as a correlating equation in table IV, it is intended to imply that the particular author used a nondimensional correlation which is one of the basic forms of equations (20) to (26), as indicated in the table. The reader is referred to the actual reference for the specific form of the correlation.

In forced convection, in addition to subdividing regions by state conditions as in figure 8, some success has been had by Yamagata, et al. (ref. 114) and others (refs. 41 and 42) in determining correlating regions by flow parameters. Figure 20 shows a typical map of heat flux against mass flow. Basically, for combinations of high flow or low heat flux, conventional correlations of the type shown in equation (9) will work even in
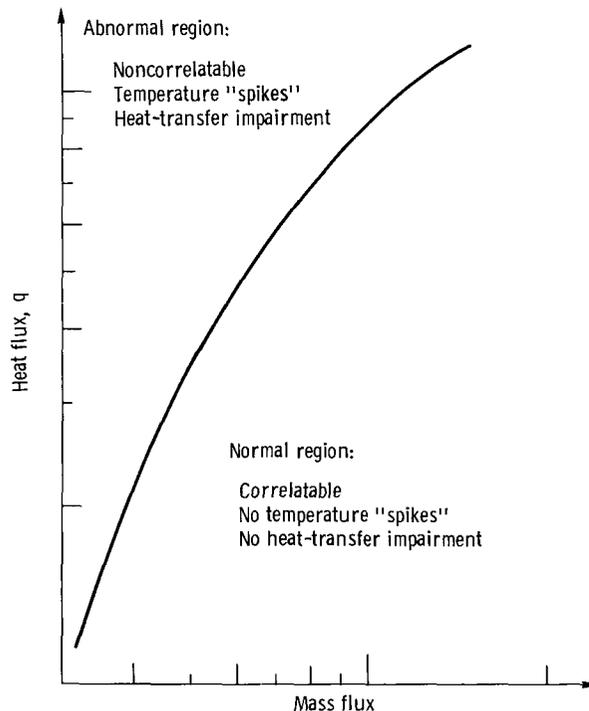
Figure 20. - Typical map of heat flux as a function of mass flux. (From refs. 74 and 114.)

region IV of figure 8. For high heat flux or low flow, however, conventional correlations fail and the peculiarities of the near-critical region, such as wall temperature spikes appear. This information helps considerably in reducing the size of the region of non-correlation (region IV). Unfortunately, for the present, only water and carbon dioxide have been explored in this manner.

Detailed investigations into mechanisms. - There have been several experiments directed to more specific and detailed information than available from the heated-tube experiments (refs. 66, 70, 73, and 113 and a paper entitled "Turbulent Heat Transfer to Carbon Dioxide Near the Critical Point" by R. J. Hanold, submitted to the 1970 International Heat Transfer Conference). Probably the most useful details concerning the flow are velocity and temperature profiles. The only experiments in which profiles have been measured were performed by Wood (refs. 66 and 115) and by Wilson (ref. 113). In both cases, they surveyed radially across a vertically oriented heated tube near the exit. Wood used carbon dioxide at an L/d of 30.7, and Wilson used hydrogen at an L/d of 128.5. Wilson's data included hot wire measurements, in addition to temperature and dynamic head profiles. In both cases, the major result was the appearance of the so-called M-shaped velocity profiles when the bulk temperature was near the transposed critical temperature, as shown typically in figure 21 and predicted analytically by Hsu and Smith. These are similar to the profiles shown in reference 116. Recent

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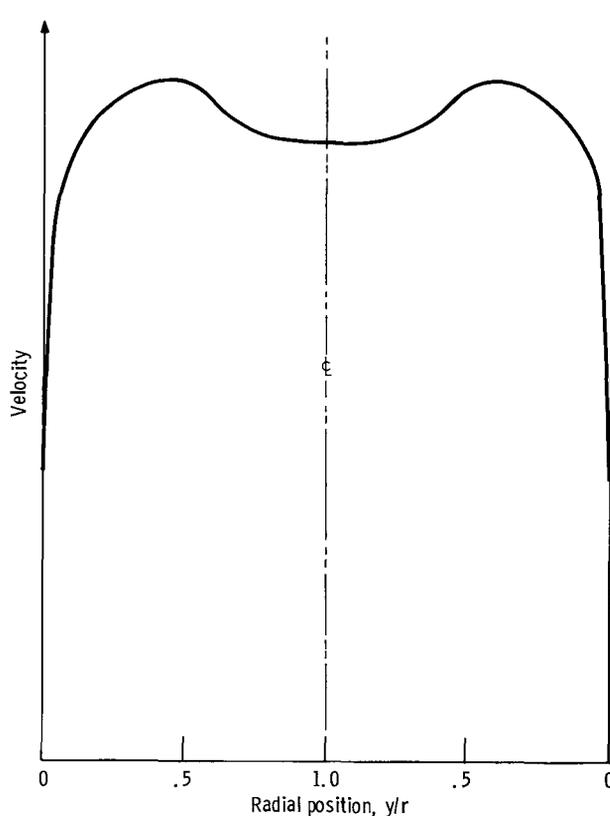
Figure 21. - Typical M-shaped profiles as found by Wood and by Wilson (refs. 66 and 113).

experiments of Bourke et al. (ref. 117) indicate the hot wire to be a useful tool in this regime.

Kahn (ref. 73) and Hanold (in the paper mentioned on p. 40), both using carbon dioxide, conducted experiments designed to isolate some of the many interacting variables and to highlight the influence of a single parameter. Kahn's method (refs. 73 and 118) was to flow carbon dioxide at its critical point between parallel plates of large aspect ratio, with one plate heated and the other cooled at exactly the same rate so that no increase in the heat content of the fluid occurred. The heat-transfer coefficient peaked sharply when the hot wall (which was always the upper wall) approached the transposed critical temperature. The peaks became sharper as the temperature difference between the walls was decreased. Hanold used a horizontal rectangular channel with one wall heated. By changing the heated wall from upward to downward, he could compare transverse body-force effect. He found a negligible difference between the two cases and attributes it to a dominance of the flow by Kelvin-Helmholtz instability as opposed to Raleigh-Taylor type.

A different result was observed by Hauptmann (refs. 70 and 119), who flowed near-critical carbon dioxide over a horizontal heated flat plate. Among his results are an in-

dication of a 30-percent increase in heat transfer for the same conditions with the heater oriented upward. Hauptmann's major contribution was a set of excellent, color, high-speed motion pictures coupled with good heat-transfer data. His data have already been discussed in figure 10.

Shiralkar (ref. 74) and Jackson (ref. 120) have reported wall temperature spikes with near-critical carbon dioxide, which are discussed in the next section.

In summary of the current, forced convection work, the following general observations can be made:

(1) Proximity to the critical point produces a sharp response in wall temperature, but the nature of the response is not uniform and the question of increased or decreased heat transfer is unclear.

(2) There is evidence of a strong similarity to boiling and there seems to be little discontinuity in going from high-pressure boiling to the supercritical region. However, since the fluid is not two phase, the formulation is somewhat arbitrary.

(3) Analyses and experiments directed specifically at critical-point heat transfer have produced some very interesting variable groupings which deserve continued investigation. Among these are

(a) Average specific heat, and integrated average properties, for example,

$$\overline{C}_p = \frac{H_w - H_b}{T_w - T_b}$$

(b) Minimum Prandtl number, $(Pr)_{min}$
(c) Eckert reference temperature parameter

$$E = \frac{T^* - T_b}{T_w - T_b}$$

(d) Turbulence enhancement factors (see the section Theoretical Considerations in Force Convection)

$$1 + \frac{\dfrac{d(\ln \rho)}{dy^+}}{\dfrac{d(\ln u^+)}{dy^+}}$$

(e) Pseudoboiling parameters such as Stermann number and Martinelli parameter

(f) Stability limit (wall temperature spikes) defined by $q = f(G)$ (see fig. 20)

(4) Despite the fact that analysts developing the various correlation or mixing length methods have been able to substantiate their work with data, subsequent investigators have usually found it necessary to modify the method to fit their own data. No analysis is currently widely accepted nor has any analysis been thoroughly tested against the available data.

Near-Critical Heat Transfer in Relation to Conventional Geometric Effects

Curved tubes. - Systematic studies of the effects of curvature on a near-critical fluid are lacking. W. S. Miller (Rocketdyne Division, North American-Rockwell) has recently completed such a study, but the data are not yet available. Several studies have been made at higher pressures and for gases. The basic effect of curvature is to instigate a secondary flow such that the boundary layer is thinned at the concave surface (see fig. 22), and thickened at the convex surface. The flow patterns indicate that the core moves toward the concave surface and then flows back along the periphery to dump in the region of the convex surface. While the classical works of Itō (ref. 121) for turbulent flows and of Dean (ref. 122) for laminar flows deal with single-phase fully developed fluids, the results of their analyses have been applied with varying degrees of success to the near-critical fluids (refs. 123 to 126 and a personal communication from W. S. Miller).

Basically, Itō found that, for high-Reynolds-number fluids, the average friction factor for a curved tube was increased over that for a straight tube by the relation

$$\frac{f_{cr}}{f_{st}} = \left[\mathrm{Re}\left(\frac{r}{R}\right)^2 \right]^{0.05} = I^{0.05} \tag{27}$$

Hendricks and Simon (ref. 123) pointed out some effects of curvature on near-critical hydrogen, which are summarized as follows:

(1) Rather conventionally, at high Reynolds numbers the concave surface enhances, and the convex surface degrades, heat transfer. The magnitude of these effects depends on fluid conditions, curvature-to-tube-radius ratio, and angular position along the bend.

(2) Visual studies with small-bend-angle tubes, using liquid nitrogen, indicate this fluid is centrifuged to the concave wall rather than swirled in the normal secondary flow
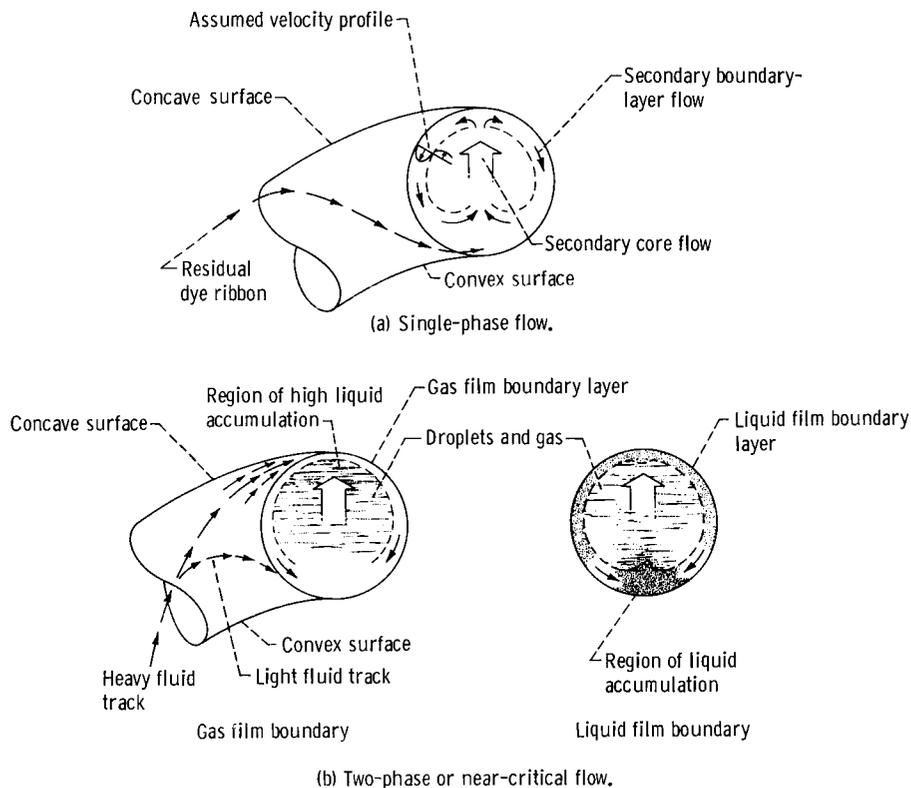
Figure 22. - Models of fluid flow in curved tubes. (Information on liquid film boundary received from K. J. Bell, Oklahoma State University.)

patterns. Visual studies with steam indicated that droplets impinge on the concave wall, flow around to the convex surface, and are carried downstream.

(3) Entrance conditions, profile similarity, and fluid history greatly influence the heat-transfer coefficients. Furthermore, the effects of curvature persist downstream of the bend and appear to be propagated upstream as well.

The magnitude of these effects appears to depend on whether the wall is "wetted." For example, little circumferential variation in h was found for some subcritical pressure hydrogen tests at low T_w/T_b.

In subsequent tests at supercritical pressure and high T_w/T_b, it was found that h could vary as though the fluid was oscillating around the tube in some harmonic manner. Such oscillations were apparently instigated by a nonuniform heat-flux pattern at the upstream heating flange. They could also be induced by other factors, such as a non-uniform inlet velocity profile, or by the secondary flow itself as it moves from the core region along the periphery back to the core region.

The effects of radius of curvature to tube radius R/r for hydrogen are shown in figure 23. At large R/r, the effect is small and approaches that of the straight tube.
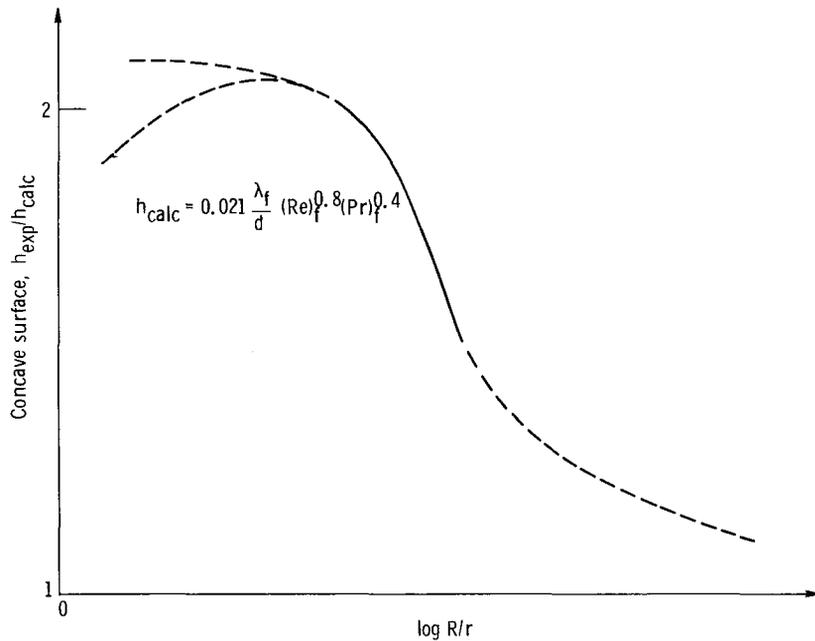
Figure 23. - Concave-surface heat-transfer coefficient as function of ratio of radius of curvature to tube radius.

At smaller R/r, the effects are quite large (2:1), but data seem to indicate two possible paths at lower R/r, as shown in figure 23. Which one is correct awaits experimental verification.

McCarthy et al. (ref. 75) investigated near-critical nitrogen tetroxide and noted a nonuniform surface temperature phenomenon along the convex surface and a persistence of the curvature effects in the downstream region. Their experiment was complicated by the dissociation of nitrogen tetroxide; however, they still found up to a 2:1 increase in h_{cv} due to curvature. In the work reported in reference 124, Thompson and Geery, investigating liquid hydrogen at $P/P_c \sim 5$, also found a 2:1 increase in heat transfer because of curvature; however, they found no effects due to asymmetrical heating on noncircular flow passages.

McCarthy, et al. (ref. 125), using hydrogen, found the heat-transfer coefficient to increase as

$$h_{cr} \propto h_{st}\left(1 + 0.1 \frac{L}{d}\right) \qquad \frac{L}{d} \le 10 \qquad (28)$$

up to $(L/d) = 10$ and to become fully developed thereafter. He suggested the following equations:

$$(Nu)_{cv} = (Nu)_{st}\left[1 + 1.867\left(\frac{r}{R}\right)^{0.519}\right]\left[0.0822(Re)_b^{0.155}\right] \tag{29}$$

$$(Nu)_{cx} = (Nu)_{st}\left[1 + 2.21\left(\frac{r}{R}\right)^{0.894}\right]\left[0.0822(Re)_b^{0.155}\right] \tag{30}$$

where $(Nu)_{st}$ is given by table IV-C of reference 55, and by equation (25).

Taylor (ref. 126) investigated the data of references 124 and 125 and found they could be adequately correlated by using Ito's parameter:

$$\frac{(Nu)_{cv}}{(Nu)_{calc}} = I_b^{0.05} \qquad \text{Concave} \tag{31}$$

$$\frac{(Nu)_{cx}}{(Nu)_{calc}} = I_b^{-0.05} \qquad \text{Convex} \tag{32}$$

where $(Nu)_{calc}$ is given as equation (9). While equations (28) to (32) were developed for hydrogen, similar correlations could be anticipated for other fluids, at high T_w/T_b values ("nonwetted" walls). "Wetted" walls and boiling have been investigated by K. J. Bell of Oklahoma State University. He found a substantial increase in h on the convex wall for wetting two-phase fluids at low T_w/T_b (private communication). The visual steam flow patterns noted by Hendricks and Simon lend credence to these results.

Twisted tapes and rifle boring. - If the bulk fluid is near the wall, an augmentation in the heat-transfer coefficient will occur. Bartlit and Williamson (ref. 127) induced swirl flow in liquid hydrogen using a twisted tape in a long tube and found the heat-transfer coefficients to be approximately those predicted by the standard Dittus-Boelter equation. This is in contrast to the same pipe without a swirl inducer, where the experimental h was much less than the predicted h (fig. 24, see also ref. 128).

E. Michaud and C. P. Welsh (Badcock and Wilcox, Barberton, Ohio) have demonstrated a similar effect with near-critical water (personal communication, see also ref. 129). The lands of a rifle-bored tube both induce swirl and trip the flow; these geometry effects eliminated the wall temperature "spike" noted in a similar smooth tube under the same conditions (fig. 25).

The enhancements, of course, require a pressure-drop penalty. J. H. Van Sant (Laurence Radiation Laboratory, University of California, Livermore, Calif.) analyzed the results of Kidd (ref. 130) and found that the enhancement in heat transfer was at the
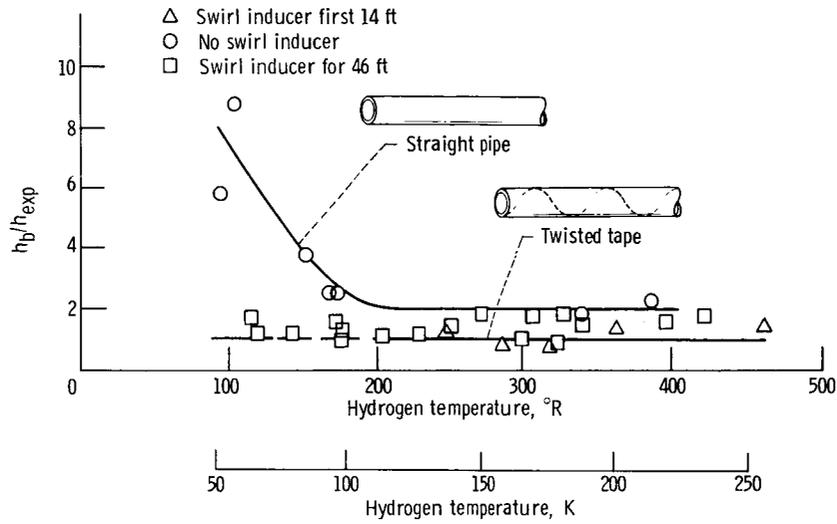
Figure 24. - Comparison of twisted-tape-insert to straight-pipe heat transfer in near-critical hydrogen. (From ref. 127).
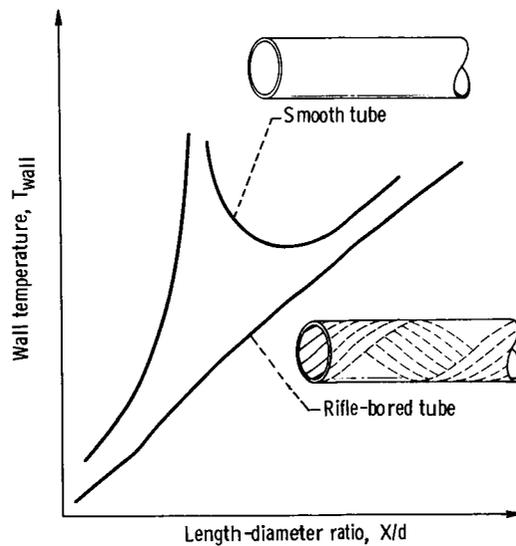

Figure 25. - Schematic comparison of rifle-bored (ribbed) tubes to smooth tubes in near-critical region. (Figure from E. Michaud and C. P. Welsh.)

direct expense of pressure drop (personal communication). The optimization of heat transfer, pressure drop, and heat-exchanger compactness requires much effort.

Body-force orientation. - Orientation of the heat-transfer apparatus with respect to gravity can have considerable influence on the results. Hall, et al. (refs. 131 and 132), Jackson and Evans-Lutterodt (ref. 120), Wood (ref. 115), and Shiralkar and Griffith (ref. 74 and 128) have found that parallel buoyancy effects can substantially alter the velocity profiles. Shiralkar et al. (ref. 74) and Jackson and Evans-Lutterodt (ref. 120) found wall temperature spikes in carbon dioxide at elevated fluxes for upward flow. In reference 120 the spikes were eliminated by downward flow. The effects also seem quite dependent on whether the bulk temperature is above or below T^*. However, the present authors found no noticeable effect with high-velocity, near-critical hydrogen in up- and downflow configurations. The first-order answer lies in the ratio of buoyancy to inertia forces which, for the authors case, was quite small $(Gr)_f/(Re)_f^2 = 4 \times 10^{-4}$. Shiralkar and Griffith (ref. 74) found the effect to be noticeable when $Gr/(Re)^2 \geq 4 \times 10^{-3}$ for water and 10^{-2} for carbon dioxide. These values and conclusions are in agreement with the computations of Hsu and Smith (ref. 133).

Transverse effects, studied by Hauptmann (ref. 70) and Hanold (in the paper cited on p. 40), have already been discussed.

Entrance effects. - Papell and Brown (ref. 134) investigated entrance effects in near-critical hydrogen. The experimental h at high heat fluxes were 1.5 times higher for an undeveloped entrance than for a hydrodynamically developed entrance, as illustrated by figure 26. This effect persisted an abnormally long distance down the tube. Little effect was found for the low-heat-flux case.
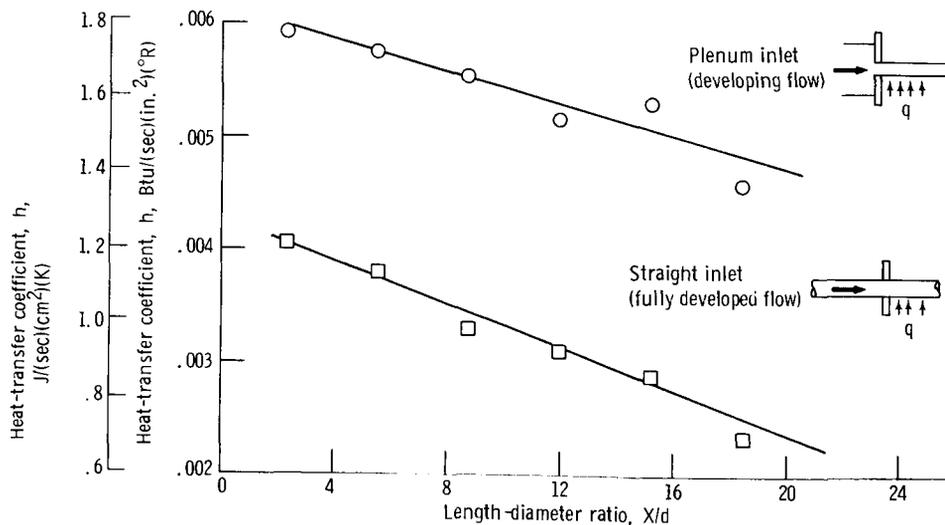
Figure 26. - Comparison of developing flow to fully developed flow for heat transfer in the entrance region with near-critical hydrogen. (From ref. 134.)

In summary, the geometric effects of significant interest in near-critical heat transfer are

(1) An increase of about 2:1 in the heat-transfer coefficient on the concave side can be expected because of curvature for gases and fluid systems at high T_w/T_b. This enhancement seems to be a centrifuging effect, particularly in small-bend-angle tubes.

(2) The magnitude of enhancement (or degradation on the convex side) appears to be related to the Itō parameter. As a reference for computing enhancement, for the "dry-wall" case, correlations of the type given in equation (9) appear to be the most satisfactory. For the "wet-wall" case, the augmentation can shift to the convex wall.

(3) Devices which centrifuge the high-density core to the wall or break up the low-density boundary layer, such as twisted tapes and spiral grooves, enhance near-critical heat transfer significantly.

(4) Experiment and analysis suggest that a parallel body force should begin to influence heat transfer when $Gr/(Re)^2 > 5 \times 10^{-3}$.

(5) Tube entrance effects persist much further down the tube in near-critical fluids than in gases.

Theoretical Considerations in Forced Convection

In the free and natural convection areas, reasonable success has been realized by using conventional variable-property approaches. For example, in natural circulation loops, the arguments of Schmidt, et al. (ref. 6) have stood the test of time and can be seen in use today in such correlating equations as equations (17) and (18). In forced convection, the fluid is not allowed to naturally seek its own circulation patterns. Consequently, the complex flow interactions caused by the rapid expansion of the near-critical fluid are superimposed on the normal forced convection patterns, and conventional forced convection approaches seem inadequate. A fair amount of analytic attention has been turned toward explaining these phenomena. This will be briefly recapped in this section.

Mixing length analyses. - By far the most widely used approach is the Prandtl mixing length concept. The basic idea is that the Reynolds stress terms of the Navier-Stokes equations can be made to look like laminar shear terms by the introduction of a turbulent viscosity or eddy diffusivity. The shear and heat flux expressions assume the popular form:

$$\tau = \eta \frac{du}{dy} + \rho\epsilon \frac{du}{dy} \tag{33}$$

$$q = -\lambda \frac{dT}{dy} - \rho C_p \epsilon_h \frac{dT}{dy} \tag{34}$$

Subject to the following nondimensionalization, Deissler (refs. 135 and 136) proposed that these equations apply throughout a supercritical flow field:

$$u^+ = \frac{u}{u^*}$$

$$y^+ = \frac{u^* y}{\nu_o}$$

$$T^+ = \frac{1}{\beta}\left(1 - \frac{T}{T_o}\right)$$

$$\beta = \frac{q_o u^*}{\left(C_p\right)_o T_o \tau_o}$$

$$\epsilon^+ = \frac{\epsilon}{\nu_o}$$

where u^* is the well-known shear velocity

$$u^* = \sqrt{\frac{\tau_o}{\rho_o}} \tag{35}$$

The nondimensional equations become, for $\epsilon_h = \epsilon$

$$\frac{\tau}{\tau_o} = \left(\frac{\eta}{\eta_o} + \frac{\rho}{\rho_o}\epsilon^+\right)\frac{du^+}{dy^+} \tag{36}$$

$$\frac{q}{q_o} = \left[\frac{\lambda}{\lambda_o (Pr)_o} + \frac{\rho}{\rho_o}\frac{C_p}{\left(C_p\right)_o}\epsilon^+\right]\frac{dT^+}{dy^+} \tag{37}$$

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Deissler (ref. 135) numerically integrated these equations for water at $P/P_c = 1.56$, with moderate success. He suggested using a reference temperature T_x (discussed in the section Heat Transfer in Forced Convection Systems) for evaluating properties, and Eckert (ref. 99) consolidated the data spread by introducing the following dimensionless temperature:

$$E = \frac{T^* - T_b}{T_o - T_b} \tag{38}$$

In that same year, Goldman (ref. 137) introduced a technique to transform the variable-density problem to the constant-density form. This was done by using a variable density in the shear velocity:

$$u^* = \sqrt{\frac{\tau_o}{\rho}} \tag{39}$$

The form of equations (36) and (37) remains unchanged, but all the nondimensional variables are changed. They are usually designated u^{++}, y^{++}, and T^{++} to indicate the change (see table V). Goldman also suggested a different form for the heat-transfer coefficient, which evolves from the Dittus-Boelter equation (ref. 138):

$$h' = \frac{q_o d^{0.2}}{G^{0.8}} \tag{40}$$

These modifications have been popular, but universal success has not been achieved.

Most of the research in mixing length theories for near-critical fluids has centered on adapting the eddy diffusivity to comprehend the near-critical phenomenon. To review the basic eddy diffusivity concept, look at two prominent examples, those of Van Driest (ref. 139) and Deissler (ref. 135):

Most eddy diffusivities ϵ can be placed into two categories: (1) continuous, and (2) multiple part. In the continuous case, Van Driest (ref. 139) argues that one form of ϵ should apply over the entire regime; while for the multiple-part case, Deissler (ref. 135) points to a near-the-wall region and an away-from-the-wall region. These and other eddy diffusivities are present in table V.

Van Driest continuous approach:

$$\epsilon = K^2 y^2 \left[1 - e^{-(y/A)} \right]^2 \frac{du}{dy} \tag{41}$$

TABLE V. - EDDY DIFFUSIVITY EXPRESSIONS

Dimensionless eddy diffusivity, $\epsilon^+ \equiv \epsilon/\nu$	Constraint	Energy-momentum solution	Reference
$$\epsilon_D^+ = \begin{cases} \left[1 - e^{-n^2(\nu_w/\nu)u^+y^+}\right]n^2u^+y^+ & \epsilon/\nu \leq 2 \\ \left[1 - e^{-K^2(\nu_w/\nu)(du^+/dy^+)^3/(d^2u^+/dy^{+2})^2}\right]K^2\dfrac{\left(\dfrac{du^+}{dy^+}\right)^3}{\left(\dfrac{d^2u^+}{dy^{+2}}\right)^2} & \epsilon/\nu > 2 \end{cases}$$	$\epsilon/\nu \leq 2$ $\epsilon/\nu > 2$	Coupled imcompressible	Deissler and Presler (ref. 213) $n = 0.124$ $K = 0.36$
$\epsilon_{VD}^+ = \left[1 - e^{-(y^+/A^+)}\right]^2 K^2 y^{+2}\dfrac{du^+}{dy^+}$	-------	Decoupled incompressible	Van Driest (ref. 139) $K = 0.4$ $A^+ = 26$
ϵ_D^+ where $u^+ \to u^{++} = \displaystyle\int_0^{u^+}\sqrt{\dfrac{\rho}{\rho_o}}\,du^+$ $y^+ \to y^{++} = \displaystyle\int_0^{y^+}\sqrt{\dfrac{\rho}{\rho_o}}\,\dfrac{\eta_o}{\eta}\,dy^+$ $\dfrac{du^+}{dy^+} \to \dfrac{\eta_o}{\eta}\dfrac{du^{++}}{dy^{++}}$ $\dfrac{d^2u^+}{dy^{+2}} \to \sqrt{\dfrac{\rho}{\rho_o}}\left(\dfrac{\eta_o}{\eta}\right)^2\dfrac{d^2u^{++}}{dy^{++2}}$ $u^+ = \dfrac{u}{\sqrt{\dfrac{\tau_o}{\rho_o}}}$ $y^+ = \dfrac{\sqrt{\dfrac{\tau_o}{\rho_o}}\,y}{\dfrac{\eta_o}{\rho_o}}$ (Note: ϵ_{VD}^+ can also be used)	-------	Coupled transform of compressible to incompressible	Goldman (ref. 78)
ϵ_{VD}^+ where $A^+ = 30.2\,e^{-0.0285\,\nu_w/\nu_b}$	-------	Decoupled	Hess and Kunz (ref. 110)
$\epsilon_D^+(1 + F_m) = \epsilon^+$ $F_m = \dfrac{\dfrac{d\ln\rho}{dy^+}}{\dfrac{d\ln u^+}{dy^+}}$ $\epsilon_D^+(1 + F_h) = \epsilon_h^+$ $F_h = \dfrac{\dfrac{d\ln\rho}{dy^+}}{\dfrac{d\ln C_pT}{dy^+}}$	-------	Coupled	Hsu and Smith (ref. 133)
$\left[\dfrac{\tau(y)}{\tau_o}\dfrac{1}{\dfrac{du^{++}}{dy^{++}}} - 1\right]\dfrac{\dfrac{1}{\rho}\left(\dfrac{\partial\rho}{\partial T}\right)_P}{\left[\dfrac{1}{\rho}\left(\dfrac{\partial\rho}{\partial T}\right)_P\right]_{T=31^\circ C}}$ (A)	-------	Coupled	Hall, Jackson, and Kahn (ref. 118); $\tau(y)$ is linear; $A = 0.4$; du^{++}/dy^{++}; conventional velocity profile
$K\left[y^+ - 11\tanh\dfrac{y^+}{11}\right]$ $\dfrac{K}{3}y^+\left[\left(\dfrac{r}{r_o}\right)^2 + 0.5\right]\left(\dfrac{r}{r_o} + 1\right)$	$y^+ < 50$ $y^+ > 50$	Decoupled	Petukhov and Popov (ref. 214) Popov (ref. 215) Reichart (ref. 216)
$\epsilon_D^+\dfrac{\sqrt{\dfrac{\rho}{\rho_o}}\,y^+}{\left[\displaystyle\int_0^{y^+}\sqrt{\dfrac{\rho}{\rho_o}}\,dy^+\right]}$	-------	Coupled	Melik-Pashaev (ref. 217)
$0.37y^+\left[1 - e^{-0.002(y^+)^2}\right]$	-------	Decoupled	Tanaka, Nishiwaki, and Hirata (ref. 65)

Deissler multiple-part approach:

$$\epsilon = n^2 uy\left(1 - e^{-n^2 uy/\nu}\right) \qquad \frac{\epsilon}{\nu} < \gamma^+ \approx 2$$

$$\epsilon = K^2\left[\frac{\left(\frac{du}{dy}\right)^3}{\left(\frac{d^2u}{dy^2}\right)^2}\right]\left[1 - e^{-(K^2/\nu)(du/dy)^3/\left(d^2u/dy^2\right)^2}\right] \qquad \frac{\epsilon}{\nu} \geq \gamma^+ \approx 2 \tag{42}$$

Equations (41) and (42) were developed primarily for constant-density analyses. They have been used successfully for variable-property gases (Deissler, ref. 135). The near-critical research has required modification of these basic forms. These modifications are summarized in table V. A few are discussed in this section.

Hess and Kunz (ref. 110) found that, for near-critical hydrogen, the damping factor of equation (41) had to include a term dependent on kinematic viscosity. Their work in this area led to the correlating equation most frequently used for near-critical hydrogen (eq. (25)).

Hsu and Smith (ref. 133) proposed that, in the presence of a strong density gradient, shear should be represented as the rate of change of momentum. The resulting eddy diffusivity expressions may be written in terms of equations (41) and (42) as

$$\epsilon_m = (1 + F_m)\epsilon$$
$$\epsilon_h = (1 + F_h)\epsilon \tag{43}$$

where ϵ is given by equation (42), and

$$F_m = \frac{\dfrac{d \ln \rho}{dy^+}}{\dfrac{d \ln u^+}{dy^+}} \qquad F_h = \frac{\dfrac{d \ln \rho}{dy^+}}{\dfrac{d \ln C_p T^+}{dy^+}} \tag{44}$$

Equation (43) reduces properly for constant density, and either form of ϵ (eq. (41) or (42)) may be used. Hsu and Smith (ref. 133) also performed a first-order force balance on a differential volume to derive an equation relating shear, buoyancy, and

pressure drop. The success of their equation in correlating the data of Bringer and Smith (ref. 100) indicates that such a modification is warranted, and is another step in the proper direction. The main problem here seems to be that, while each researcher has success correlating his own data, subsequent researchers had troubles. Further, Hall (ref. 131) using several different techniques on the data of Koppel (ref. 140) also found a degree of insensitivity in the theories, as illustrated in figure 27.

Hall (ref. 132) developed a model for flow in a vertically oriented pipe or channel in order to demonstrate some of the buoyancy effects which have been found with near-critical fluids (see the section Body-force orientation). Halls' theoretical approach, while limited and analogous to the two-phase or two-component flow approach, merits attention because it isolates some governing parametric forms. The first model assumes a discontinuous change in transport properties and density at $y = \delta$, with "gas-like" properties at $y < \delta$ and liquid properties for $y > \delta$ (e.g., see fig. 28). The shear distribution is a two-part linear form (see fig. 28). The velocity profile is lami-
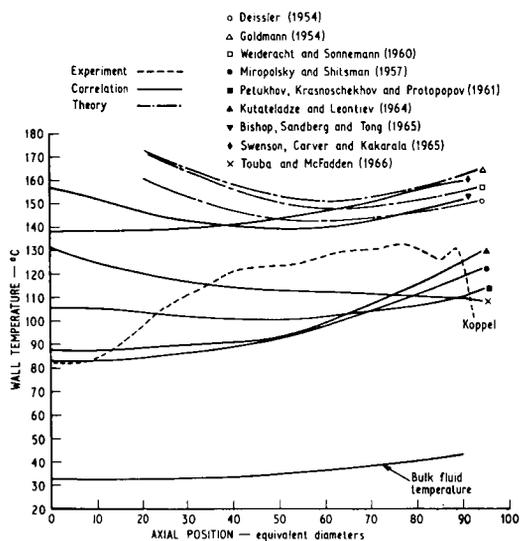
Figure 27. - Comparison of various correlations and mixing length theories to carbon dioxide data of Koppel. Ratio of pressure to critical pressure, 1.028; mass flow rate, 92.2 grams per centimeter per second; heat flux, 22.5 joules per centimeter squared per second; characteristic diameter, 0.493 centimeter. (Reproduced from ref. 131.)
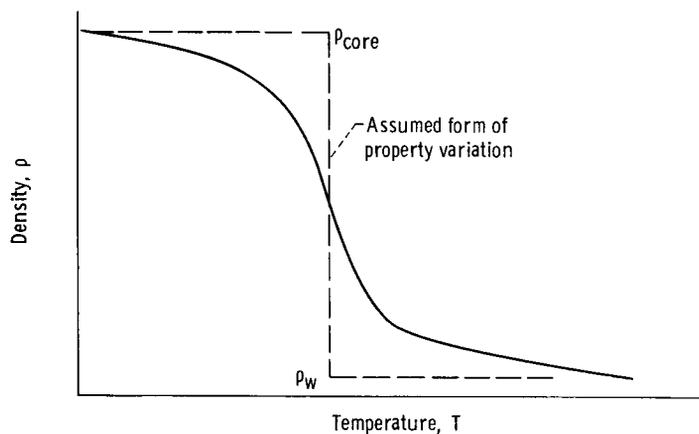
(a) Property variation.
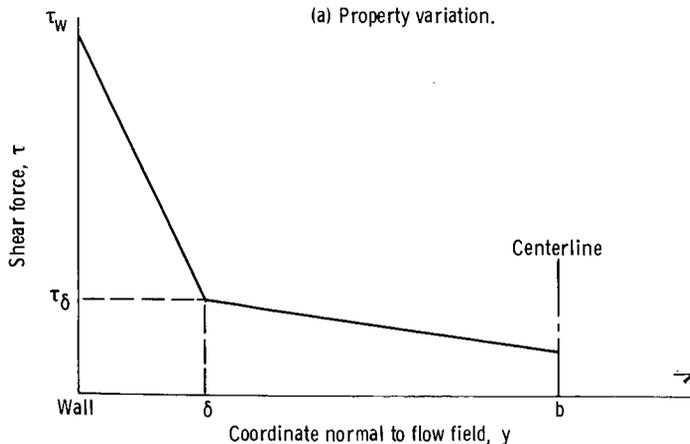
(b) Shear distribution.

Figure 28. - Property variation and shear distribution for the models of Hall (ref. 132).

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nar for $y \leq \delta$ and follows the conventional velocity defect law for $y > \delta$. With these assumptions, the momentum equation

$$\frac{dz}{dy} = \frac{\Delta p}{\Delta X} + \rho g$$

where $\Delta p/\Delta X$ = Constant, can be reduced to

$$\frac{\tau_\delta}{\tau_w} = 1 - \frac{(Gr)'}{\left(b_H^+\right)^2} \xi$$

Here $b_H^+ = y^+$ evaluated at the tube radius or channel half width, $\xi = \delta/b_H$, and $(Gr)' = \rho_w(\rho_{core} - \rho_w)gb_H^3/\mu_w^2$ is the conventional Grashof number as defined for two-phase or two-component flows.

In the second model, Hall (ref. 132), employed equations (36) and (37) with Van Driest's eddy diffusivity, equation (41). However, the shear stress distribution τ/τ_0 was assumed to be of two parts (see the Deissler approach, eq. (42)):

$$\frac{\tau}{\tau_0} = 1 - \frac{y}{b_H}\left[1 + (1 - A_1)\left(\frac{1 - \xi}{\xi}\right)\right] \quad \text{near the wall}$$

$$\frac{\tau}{\tau_0} = \left(1 - \frac{y}{b}\right)A_1 \quad \text{in the core}$$

where $A_1 = \tau_\delta/\tau_w$. Hall (ref. 132) found little difference in the results given from the two models, which reinforces an earlier remark regarding the insensitivity in the theories. Hall and Jackson (ref. 141) and Leontiev (ref. 142) have tried to relate this phenomenon to that of lamarization.

Each theoretical technique has a great deal of merit and correlates the data presented in each author's respective papers. Using near-critical hydrogen, we at NASA and also Szetela (ref. 143) have tried the techniques of Deissler (refs. 135 and 136) and Goldman (ref. 137) with very limited success. The technique of Hess and Kunz (ref. 110) was tried, and success was limited, in the main, to those data with bulk temperatures above the T^* regime. The integral average property approach of Goldman (ref. 137) gave similar limited results. The modifications of Hsu and Smith (ref. 133) and Brokaw (ref. 109) were also tried again, with only limited success. Modifications of the modifications, such as using different dampening factors, including upstream effects, etc., were also attempted; however, the results were very disappointing.

The solution of equations (36) and (37) (or modifications, eqs. (43) and (44)) involves the iteration of a numerical integration to attain a solution. The iteration is required to satisfy the continuity equation and to determine one parameter. In pipe flow, this parameter can be $\beta = q_o u^* / \left(C_p \right)_o \tau_o T_o$, τ_o, or r^+. However, r^+ is usually fixed at the pipe centerline and τ_o is considered to be known; thus q_o and T_o remain as adjustable constants, within the parameter β. In the boundary-layer flows, at the edge of the boundary layer δ^+, either β or τ_o can be considered to be the parameters; usually δ^+ is altered at a fixed β and τ_o to give the solution. The point is that for near-adiabatic flow of a gas there exists an adjustable parameter to force a solution to the problem. However, this freedom becomes compounded when applying these equations in the near-critical region because the following factors are not known:

(1) Does $\epsilon / \epsilon_h \to 1$? (Some of the best results for near-critical fluids in a pipe attained by the authors (unpublished computer programs by Robert C. Hendricks) were for $\epsilon / \epsilon_h > 1$.
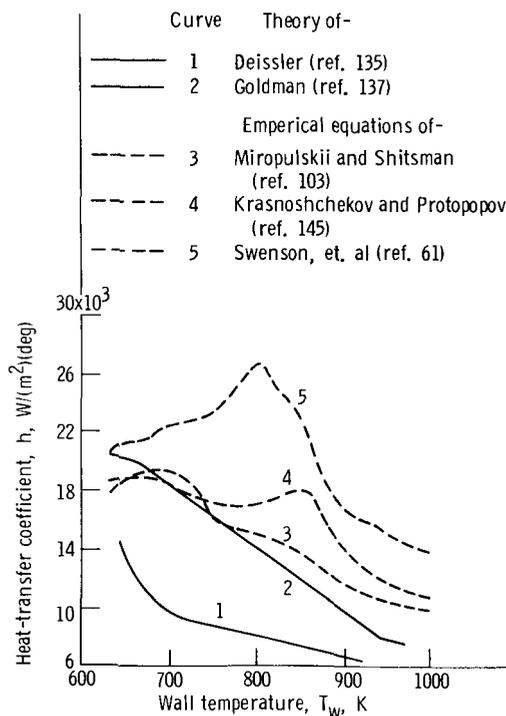
Figure 29. - Heat-transfer coefficient as function of wall temperature for water. Pressure, 345 atmospheres (at 417° C); ratio of wall temperature to film temperature, 1.25; mass flow, 2150 kilograms per square meter per second; characteristic length, 9.4 millimeters. (From ref. 144.)

(2) Are the expressions for ϵ or ϵ_h correct?

(3) Is the functional form of τ/τ_0 and q/q_0 realistic (i. e., constant, linear, cubic, etc.)?

(4) Do the convective terms in the momentum and energy equations significantly alter the results? These terms are considered in the next section.

In view of these unknowns, several different velocity and energy distributions may integrate out to give the same solution. However, the convergence may be quite slow and difficult to achieve; and furthermore, the result may be meaningless.

Some of these difficulties have also been encountered by Petukhov. In a recent survey article (ref. 144), he lists three basic difficulties in attaining solutions for heat transfer in the near-critical regime:

(1) The nonlinearity of the governing equations with variable properties

(2) Ignorance of the laws of turbulent heat transfer with variable physical properties: To determine these laws will require detailed profile measurements in the near-critical regime - a task of considerable difficulty.

(3) Difficulty of interpretation and generalization of near-critical data because heat transfer and pressure losses are functions of many variables

In figure 29, Petukhov (ref. 144) compares the theoretical results of Deissler (ref. 135) and Goldman (ref. 137) and the empirical equations of Miropulskii and Shitsman (ref. 103), Krasnoshchekov and Protopopov (ref. 145), and Swenson, et al. (ref. 61).

Petukhov (ref. 44) points out that the theoretical analyses are in considerable disagreement with the experimental results although no data are given in figure 29 for comparison. In reference 144, Petukhov also presents an analysis of Popov which is valid, unfortunately, only for carbon dioxide data. Petukhov (ref. 144) classifies the near-critical heat-transfer regimes as

(1) Normal: where the dependence of Nu on Re and Pr is approximately the same as for the constant properties case

(2) Reduced heat transfer: where $T_{bulk} < T^*$, and certain combinations of mass flow and heat flux lead to a sharp decrease in heat transfer and a rapid increase in the wall temperature

(3) Improved heat transfer: where $T_{bulk} < T^*$, with oscillations of sufficient amplitude ("whistling") and high frequency (1400 to 2200 Hz) at higher heat fluxes to cause a flattening of the axial wall temperature profile

These classifications are in agreement with those presented herein but, perhaps, are formulated in a different manner.

Acceleration - strain rates. - Deissler (ref. 146) found the strain rate (acceleration or deceleration) to be important in turbulent heat transfer. For example, the strain effects of longitudinal acceleration on homogeneous turbulence intensities are shown in figure 30. The ordinate is the square of the turbulence intensity of the transverse veloc-
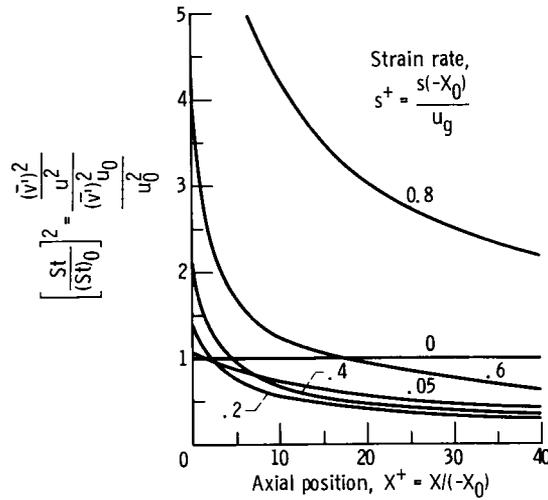
Figure 30. - Effect of acceleration or longitudinal strain on heat transfer for positive strain rates. (From ref. 146.)

ity component normalized with respect to an initial intensity condition $\left[\overline{(v')}^2/u^2\right]/$ $\left[\overline{(v')}^2_{u_0}/u^2_0\right]$. It can be shown that this dimensionless parameter is related to the square

of a Stanton number ratio $(St)/(St)_0$ where the denominator is the initial Stanton number before acceleration

$$\left[\frac{St}{(St)_0}\right]^2 = \frac{\dfrac{\overline{(v')}^2}{u^2}}{\dfrac{\overline{(v')}^2_{u_0}}{u^2_0}} = f\left[\dfrac{\dfrac{du}{dX}}{\left(\dfrac{du}{dX}\right)_0}\right] \qquad (45)$$

The abscissa of figure 30 is axial position; the parameter s^+ is a strain rate. Figure 30 shows that the local intensity, or Stanton number, progressively decreases when subject to a strain rate.

Under heating conditions, a near-critical fluid would undergo large longitudinal accelerations while expanding in a constant-area pipe. Experiments by Weiland (ref. 147) and Taylor (ref. 148) with gases at high heating rates suggest that such expansion effects occur. Deissler (ref. 146) showed that the data trends in references 147 and 148 could be explained by strain or acceleration effects. Such an analogy could also be drawn for the laminarization data of Moretti and Kays (ref. 149). Perhaps some of the unusual

Figure 31. - Concept of simultaneous hydrodynamic and penetration mechanisms. (From ref. 150).

distributions of heat-transfer coefficient noted for near-critical hydrogen (refs. 41 and 134) relate to strain effects.

Penetration model. - An analogy between heat transfer in fluidized beds and near-critical forced convection has been suggested by Graham (ref. 150). Using the penetration theories of fluidized beds, Graham proposed a penetration model for near-critical fluids. The mechanism (see fig. 31) was assumed to be a disruption of the sublayer by the periodic migration of fluid packets from the outer edge of the boundary layer to the wall, where they absorb energy in a transient manner. The average heat-transfer coefficient can then be expressed as a linear sum of the conventional film-heat-transfer coefficient and a penetration coefficient with the proper area weight fraction assigned to each

$$h_{av} = \frac{\mathscr{A}_p}{\mathscr{A}_{tot}} h_p + \left(1 - \frac{\mathscr{A}_p}{\mathscr{A}_{tot}}\right) h_f \tag{45a}$$

where

$$h_p = \frac{2}{\pi} \sqrt{\frac{(\rho c_p \lambda)_b}{\tau_{contact}}} \tag{45b}$$

The theory suffers from the lack of a theoretical means of determining $\tau_{contact}$, but has the distinct advantage of reducing to the proper expression outside the near-critical region and integrates the physics of the near-critical problem in a realistic manner. The technique has been used to correlate near-critical hydrogen, carbon dioxide, and water data.

In summary, the theoretical investigation in forced convection in the near-critical region suggests

(1) Conventional mixing length theories must be modified to account for the tremendous fluid expansion in the near-critical region. These modifications could be in the equations, following Goldman's example (ref. 137); or in the eddy diffusivity, following Hsu and Smith (ref. 133); or in forming a penetration mechanism, Graham (ref. 150).

(2) Applications of these and other modifications of mixing length theory to near-critical data have met with limited success. The theory will probably also have to be made to comprehend upstream history, acceleration, etc., in order to achieve wide success.

(3) Further analysis of accelerated flows should consider the effects of strain rates. While the theory of Deissler predicts the proper trends, the magnitudes associated with a real near-critical fluid are not correct. Thus, the boundaries and the variation in fluid properties must be properly considered (not an easy task).

Oscillations

General remarks. - Fluid oscillations play a major part in near-critical phenomena, and several heat-transfer studies (refs. 42, 75, 98, 125, and 151 to 153) have reported some type of instability in natural and forced convection systems. The frequency of reported oscillations varies from 1/20 to 10 000 hertz over a considerable range in amplitude (as high as 0.3 of test pressure). The higher-frequency oscillations, 300 to 10 000 hertz, seem to be associated with longitudinal and lateral oscillations - a gas-like fluid behavior; and the lower-frequency modes are most common to the near-critical region. Thus, discussion is restricted mainly to the low-frequency spectrum.

Fluid behavior in the two-phase and near-critical regimes appears to be similar, and different modes of oscillations have been identified and analyzed. The analyses have been successful in predicting the onset and frequency of oscillation but less so in predicting the amplitudes. Flow excursions, as well as periodic flows, have been studied
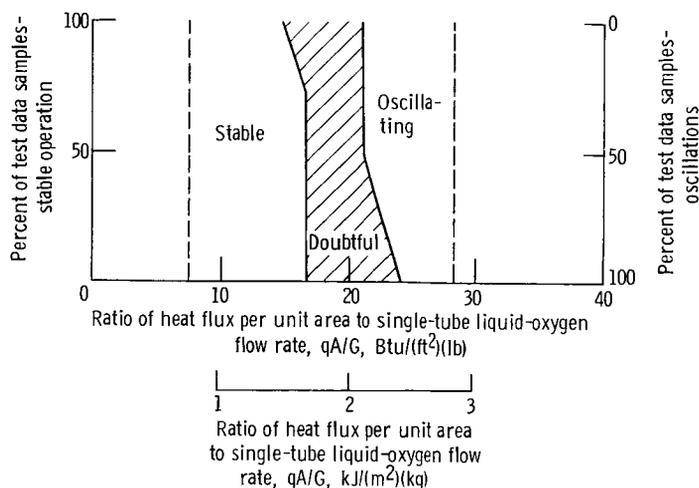
Figure 32. - Percentage of heat-exchanger-test data samples showing
steady operation against heat flux per unit area for unit mass flow rate.
Single-tube data coil pressure, 40 to 47.5 atmospheres. (From ref. 39.)

by Zuber (ref. 39). Similar oscillations in natural and forced convection have been re-
ported. Several authors after observing oscillations (refs. 39 and 41) have delineated
correlatable and noncorrelatable data based on mass flow rate and heat flux, as illus-
trated in figure 32 (see also fig. 20).

Oscillations in the near-critical regime have the common characteristic of persist-
ence for a significant period of time. This means they occur at, or very near, a natural
frequency of the system, and the damping forces are insufficient to quickly arrest them.

Oscillations may be divided into four types, of which three may be separated by their
frequencies. The other type is associated with the oscillation of a near-critical fluid be-
tween laminar and turbulent flow. Due to the sensitive nature of near-critical fluids to
fluctuations, the laminar-turbulent oscillations may be characteristic of any heat-
transfer system of equal sensitivity. These oscillations were discussed in the section
Heat Transfer in Free Convection Systems.

The other three types of oscillations may be classified as (1) thermal-acoustic
(5 to 300 Hz); (2) system oscillations (1/20 to 5 Hz), which are concerned with the be-
havior of all the fluid in a loop or system; and (3) external oscillations (e.g., in pipes,
in fluid conduits, and in valves). This latter type would be induced and sustained by the
equipment and have a frequency which is that of the static system. They will not be dis-
cussed further.

Examples of both thermal-acoustic and system oscillations are shown in figure 33.
These oscillations appear to have a significant density change as the source of their be-
havior, which is characteristic of the onset of the two-phase and near-critical regimes.
Here, the density change becomes very sensitive to further additions in energy or
changes of temperature. Generally, oscillations will occur when the bulk of the fluid is
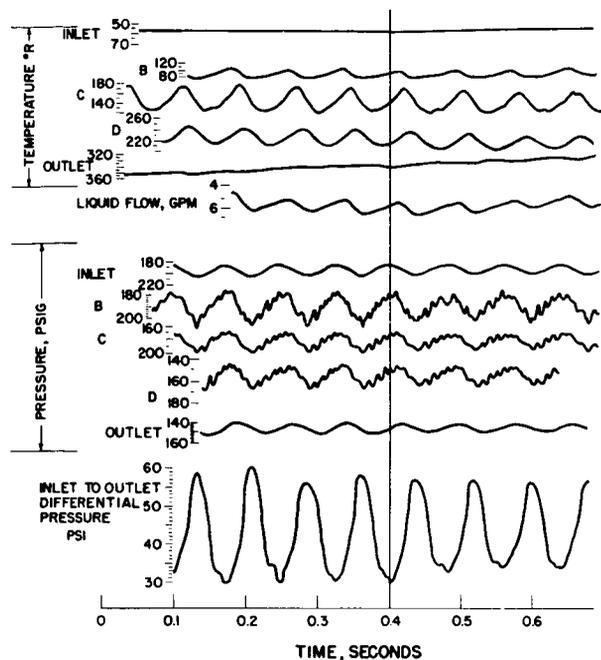
(a) Thermal-acoustic oscillations (ref. 40).
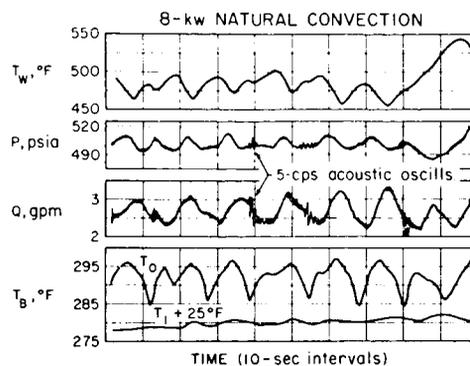
(b) System oscillations (ref. 151).

Figure 33. - Examples of thermal-acoustic and system oscillations reproduced from references 40 and 151.

in a liquefied condition and the boundary layer appears to be occupied by a lower-density fluid. Most analyses of oscillations assume density to change abruptly at the saturated liquid and vapor points and at the equivalent points in the near-critical region. This assumption tends to more sharply define the oscillating behavior.

Thermal-acoustic oscillations. - The thermal-acoustic oscillations (5 to 300 Hz) may be assumed to occur from localized events, in contrast to those of the fluid-body type, which involve the motion of the entire fluid system. Thurston (ref. 152) identified two types of these oscillations in his forced convection system. The first type is a Helmholtz oscillation, which is associated with a cavity connected to a large plenum, such as the atmosphere, with a substantial restriction between the two elements. The natural frequency of this system may be expressed by the equation

$$W_n = \frac{\mathscr{A}}{2\pi} \left(\frac{\gamma P}{mV_g}\right)^{1/2} \tag{46}$$

This Helmoholtz resonance has not been reported in most of the systems concerned with this type of study and may be presumed to occur only when the system obviously fits the analytical assumption rather closely.

The second type of acoustical oscillation is a sonic-wave resonance, identified by

Thurston and others, and is associated with the velocity of sound and the length of fluid in the flow loop or fluid system considered. The natural frequency of this system may be expressed by the following equation:

$$W_n = \frac{c}{2L'} \tag{47}$$

The period for these oscillations is that time required for the acoustic wave to tranverse one-half the fluid length. The frequency of these oscillations has been found experimentally to be a very weak function of heating rate, and appropriately it changed with fluid length.

Several authors have proposed mechanisms which would produce and reinforce these acoustic oscillations. These mechanisms examine the behavior of the boundary layer during the passing of a pressure wave. Thurston (ref. 152) suggested that such a wave would tend to compress the boundary layer, improve its thermal conductivity, and cause an increased heat-transfer rate. Immediately following this process there would be a tendency for the boundary layer to expand, with a subsequent decrease in thermal conductivity and decreased heat-transfer rate. This mechanism would reinforce the acoustic wave as it proceeds through the field.

Thurston, et al. (ref. 40) developed two similarity parameters to determine the onset and amplitude of the thermal-acoustic oscillations. One is a function of the Stermann parameter (boiling number) and the other a function of properties, fluid conditions, flow rate, and geometry of the system.

Thurston, et al. (ref. 40) proposed that the onset of these oscillations can be empirically determined as a relation between the Stermann parameter and the specific volume number described by the following expression:

$$Sr \leq 0.0045(Sv)^{-0.75} \tag{48}$$

where

$$Sr = \frac{q_0}{Gh_{fg}^*} \tag{48a}$$

and

$$Sv = \frac{v_{fg}^*}{v_f} \tag{48b}$$

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The locus of the onset of oscillations is described by the equality in equation (48) $(Sr)_o$ and the stable points by the inequality. Other authors have identified this threshold by applying stability criteria to the fluid system, employing the general conservation equations.

The amplitude parameter developed by Thurston was roughly correlated as a function of Stermann number

Amplitude parameter:

$$Am = \frac{p^* W_n d}{G h_{fg}^*}$$ (48c)

Amplitude correlation:

$$Am = 0.011 \left[Sr - (Sr)_o \right]^{0.66}$$ (49)

System oscillations. - Thermal-ascoustic oscillations are confined to the heater section, while system oscillations involve the motion of the fluid in the entire loop. System oscillations (1/20 to 5 Hz) seem to be present to some degree in nearly all near-critical heat-transfer experiments.

Thus, while the thermal-acoustic oscillations may have a significant amplitude and this, in turn, may affect the heat-transfer and general system behavior, most facilities will not fail to function because of their presence. System oscillations however, could very conceivably prevent the operation of the loop in several different ways (e.g., a pressure variation effecting cyclic heat-transfer conditions to produce forces which may cause mechanical failure). The frequency of these oscillations is somewhat lower than for the thermal-acoustic oscillations. Also, they are one function of the energy input to the fluid, and another function of the system geometry.

Analysis of system oscillations, whether in a two-phase or in a supercritical region, tend to assume a boiling-like phenomenon with substantial density changes. The basic approach is to supplement the time-dependent, one-dimensional conservation equations (continuity, energy, and momentum) by an equation of state which exhibits a discontinuity at the saturated liquid line or at the equivalent point in the near-critical regime. Two general methods have been used to predict the onset of these oscillations. The first, attributed to Craya and Bouré (ref. 154), is called the density effect model. This method has been used and extended by a number of authors (refs. 155 to 157). Walker and Harden (ref. 156) found six independent variables which would influence the inception point. Three of these are concerned with geometry and the friction factor

which could be considered essentially constant for any given system. The remaining three variables are fluid velocity, gravitational force, and subcooling. The critical frequency, the same as that of an oscillating manometer, is given by

$$W_n = \frac{1}{2\pi} \left[\frac{2g(\rho_f - \rho_g)}{c(\rho_f + \rho_g)} \right]$$ (50)

Walker and Harden (ref. 157) were able to compute a threshold surface involving the three variables and to predict instabilities in a Freon-114 natural convection loop with good reliability.

The second criteria used the Nyquist-type of test to determine the stability of the system. This method is widely used for electrical systems and can be employed in fluid systems by utilizing analogous behavior. For example, the resistance and capacitance of fluid system components can be modeled electrically. Examples of such modeling can be found in the work of Zuber (ref. 39), Friedly et al. (ref. 158), and Wallis and Heasley (ref. 159). Examples of working heat-exchanger oscillations are found in reference 160.

The following remarks can be made in summary:

(1) Oscillations in near-critical flow can be divided into four groups: laminar to turbulent, thermal acoustic, system, and external.

(2) The large density changes of a near-critical fluid are the basic source of the oscillating behavior.

(3) The critical frequency for the thermal-acoustic and system oscillations can be predicted by utilizing simple concepts of mechanics.

(4) Conventional stability criteria may be employed to predict the thermal-acoustic and system oscillations with a fair degree of reliability.

(5) Attempts to predict the amplitude of the oscillations has met with only limited success.

Choking Phenomenon

Although the authors are aware of only one reported work and their own current work on this subject, choking flow in the near-critical region may be unique and of considerable interest. Choking flow, often referred to as critical flow, may be defined as the condition where the mean velocity and the mass flow rate are at a maximum with respect to further reductions in the downstream pressure (refs. 161 and 162).

W. G. Zinman, in a private communication, points to the observed similarities in various critical phenomena (e.g., choked flow, detonations, shock waves, critical points of ferromagnets, thermodynamic critical point) and suggests there should be some com-

mon theoretical base for each system. For example, the thermodynamic critical region and choking flows are essentially unstable phenomena, and experimental measurements to determine either are destined to some degree of failure. The experimental problems encountered in obtaining data for either of these critical conditions are monumental. As critical conditions are approached, changes occur very rapidly. In the thermodynamic critical region, these are property changes; and in choking flow, they are usually characterized by pressure changes in the flow direction. Because of these very rapid changes, relaxation times become important. It follows that for many systems, at the rates of change required to maintain equilibrium, it is unlikely that equilibrium will be achieved nor can the system be assumed to be frozen. Therefore, the problem of choking flow near the thermodynamic critical point is compounded by the necessity of considering two critical and elusive phenomena combined.

For a single-phase, homogeneous fluid, the critical flow rate may be described by

$$G^2 = -\left(\frac{\partial P}{\partial v}\right)_{process} \tag{51}$$

If the process is assumed to be isentropic, the choking velocity is equivalent to the sonic velocity.

If it is assumed that the fluid is homogeneous in properties and velocity and in thermal equilibrium at the critical point, the choking and sonic velocities as described by $u^2 = \partial P/\partial \rho$ would be zero. This is because the derivative in equation (51) goes to zero at the critical point. Also, in the near-critical region, the value of this derivative tends to be quite low. Some experimental work reported by Williamson and Chase (ref. 163) gives the measured sonic velocity of helium in the near-critical region. This is shown in figure 34. Examination of the figure shows that, indeed, the velocity does appear to approach zero near the critical point and to be at a relatively low minimum in the region of the transposed critical. Van Dael, et al. (ref. 164) reported similar results for argon. Further, they indicate a practical lower limit on sonic velocity of about 100 meters per second.

It would appear that if, indeed, the very low choking velocities were probable in the near-critical region, some experimental measurements (a discontinuous pressure profile accompanied by abnormally large pressure loss, or visual observations) would have been reported which would indicate the presence of choking flow in the system. Since none of these conditions has been reported in the near-critical fluid flow and heat-transfer studies, it must be assumed that the choking velocities are somewhat higher than those indicated by the sonic velocity or by studies which assume thermal equilibrium with a homogeneous fluid. The work of Hesson and Peck (ref. 165) with carbon dioxide appears to be the closest to the critical region. Hesson and Peck mapped two-
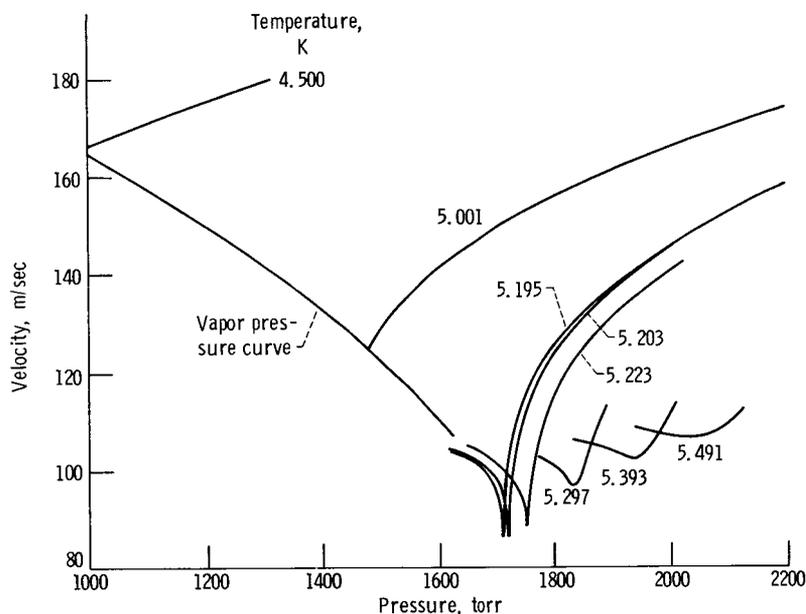
Figure 34. - Overall view of sound velocity of helium-4 as function of pressure near critical point. (From ref. 163.)

phase critical flow for stagnation pressures up to the critical; however, no data were taken above critical pressure or for throat pressures in the near-critical region. A similar experimental program for nitrogen flowing in a converging-diverging nozzle is currently under way at Lewis Research Center (unpublished data by R. E. Henry, R. J. Simoneau, R. C. Hendricks, and R. Watterson). Preliminary data have been taken for stagnation temperatures ranging from 85 to 128 K and for stagnation pressures in the range of 26. 4 to 41. 8 atmospheres. These results indicate that the choking phenomenon in this region is characterized by a nonequilibium expansion. In addition to the conditions listed, the stagnation pressure range will be extended to 68 atmospheres in an attempt to create near-critical conditions at the nozzle throat.

For the two-phase-flow case, which should represent an extreme of the near-critical two-species choking flow, it has been shown that assumptions of nonequilibrium or of different phase velocities are necessary to explain the experimental data (refs. 166 to 168).

In summary it can be said that

(1) If a near-critical fluid were in thermodynamic equilibrium, the sonic velocity would be low and the flow might be expected to choke very easily.

(2) None of the normal indications of choking have been observed in the near-critical experiments. This suggests the possibility of thermodynamic nonequilibrium in these flows, which is also consistent with two-phase choking experience. Preliminary nozzle data for near-critical nitrogen indicate the expansion to be nonequilibrium.

Zero-Gravity Operation

The authors are aware of only one qualitative heat-transfer study of a near-critical fluid at very low gravity. Potter and Brill (ref. 169) placed 2.5 liters of liquid nitrogen on an Atlas ballistic flight. They present data for nearly 1500 seconds, during which time the gravity force increased from 6×10^{-4} to 0.1034 g's. Liquid-nitrogen pressure level was controlled by an internal heater and periodic flows. Although Potter and Brill report that zero-gravity operation of the vessel was not significantly different from earthbound tests, their pressure profiles do indicate some differences. Data in this area are lacking and work should be performed.

SUMMARY OF RESULTS

Various areas of research on near-critical heat-transfer have been surveyed. The results for each area have been summarized at the end of that particular section. These summaries are repeated here for the convenience of the reader.

Fluid Properties

1. Classical Van der Waals models do not accurately describe the state of a near-critical fluid, but may be satisfactory in first-order considerations.

2. The discrepancies in the law of corresponding states are accentuated in the critical region, and the law should be used only between fluids of similar molecular structure.

3. A thermally disturbed near-critical fluid requires long relaxation times to return to equilibrium.

4. Equations of state of the conventional virial type can be made to accurately map a near-critical pressure-density-temperature surface; however, they are not good for thermal properties requiring derivatives of the equation of state.

5. A new analytic equation of state involving chemical potential, density, and temperature, based on the Ising lattice gas model, has been developed for the near-critical region.

6. The evidence for the existence of a strong anomalous spike in thermal conductivity at the critical point is overwhelming. The spike can be estimated by treating the fluid as a dissociating polymer and superimposing the results on the conventional $\lambda - \lambda^* = f_1(\rho)$ curve (eq. (5)), where λ is thermal conductivity, λ^* is the thermal conductivity at low pressure, and $f_1(\rho)$ is a function describing variations in thermal conductivity.

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7. If a similar spike occurs in viscosity, it is sufficiently weak to be ignored. Thus, $\eta - \eta^* = f_2(\rho)$ (eq. (6)) will adequately describe viscosity, where η is viscosity, η_0 is viscosity at low pressure and $f_2(\rho)$ is a function describing variations in viscosity.

8. Pseudo-two-phase thermal properties can be generated by extrapolation of saturation properties into the near-critical region.

Heat-Transfer Regions

1. The near-critical heat-transfer region and its adjacent regions can be delineated in an approximate manner on a temperature-entropy state diagram.

2. It is not possible to set precise near-critical heat-transfer boundaries for the following reasons:

(a) Data are generally insufficient.

(b) The transition from region to region is not abrupt.

(c) Most important, the extent of influence of the critical point on heat transfer is a function of the process or path by which the fluid approaches the critical point.

3. Heat transfer in the adjacent regions can be correlated by conventional methods appropriate to that region. In fact, the correlatable nature of the adjacent regions helps determine the near-critical boundaries.

Near-Critical Heat-Transfer Pecularities

1. Some characteristics of the near-critical region are

(a) Nonlinearities in heat flux against temperature difference

(b) Wall temperature excursions (spikes)

(c) Similarities to the two-phase regime

(d) Oscillations

(e) Large momentum pressure drops

(f) System-dependent results

(g) Failure of conventional correlations

2. Modeling should be required to work throughout region IV, and to exhibit a smooth transition to the adjacent regions of figure 8.

Free and Natural Convection

1. Pool results almost universally show an enhancement in heat transfer near the critical point. In all cases, the temperature differences are small and the enhancement occurs over a limited temperature range and peaks somewhat away from the critical point. Large temperature differences diminish the peak.

2. Free convection systems have no constraining boundaries and consequently respond favorably to property variations.

3. Boiling-like behavior in near-critical pools is not accompanied by the marked increase in the heat-transfer coefficient associated with nucleate boiling.

4. Most researchers employed conventional techniques away from the critical point. However, close to the critical point, modifications such as equations (15) and (16) are employed (see table II).

5. Laminar-to-turbulent oscillations have been observed, but the origin of this phenomenon has not been explained. These oscillations may well determine the character of near-critical oscillations found in natural and forced convection systems.

Loops - Natural Convection Systems

1. In the free convection pools and natural convection loops, close proximity of the fluid to the critical point appears to enhance heat transfer. This is possibly the result of a free boundary system being able to respond to enhancing property variations where the temperature differences are low. As will be shown, forced convection systems at low temperature differences exhibit similar trends.

2. Reasonable success has been achieved in correlating the data of both the pools and natural convection loops by variable property modifications to the standard equations for the given configuration.

3. The pool experiments have produced considerable support for a pseudo-two-phase modeling of a near-critical fluid. On the other hand, the success of single-phase correlations indicates either approach may be successful.

4. To date, no single correlation has been tested against all the available data.

5. Since these experiments operate very close to the critical point, there is a continuing need for improved property data and equations of state.

6. System oscillations which are commonplace in a natural convection loop near the critical point are similar to those observed in forced convection systems.

Forced Convection - Experimental

1. Proximity to the critical point produces a sharp response in wall temperature, but the nature of the response is not uniform and the question of increased or decreased heat transfer is unclear.

2. There is evidence of a strong similarity to boiling and there seems to be little discontinuity in going from high-pressure boiling to the super-critical region. However, since the fluid is not two phase, the formulation is somewhat arbitrary.

3. Analyses and experiments directed specifically at critical-point heat transfer have produced some very interesting variable groupings which deserve continued investigation. Among these are

(a) Integrated specific heat $\overline{C_p}$, and other integrated average properties,

$$\overline{C_p} = \frac{H_w - H_b}{T_w - T_b}$$

where H_w and H_b are wall and bulk enthalpy, respectively, and T_w and T_b are wall and bulk temperature, respectively.

(b) Minimum Prandtl number $(Pr)_{min}$

(c) Eckert reference temperature parameter

$$E = \frac{T^* - T_b}{T_w - T_b}$$

where T^* is the transposed or pseudocritical temperature.

(d) Turbulence enhancement factors (see the section Theoretical Considerations) such as

$$1 + \frac{\dfrac{d(\ln \rho)}{dy^+}}{\dfrac{d(\ln u^+)}{dy^+}}$$

where ρ is density, y is the coordinate normal to the flow field, y^+ is dimensionless distance, and u^+ is dimensionless velocity.

(e) Pseudoboiling parameters such as Stermann number and Martinelli parameter

(f) Stability limit (wall temperature spikes) defined by

$$q = f(G) \qquad \text{(see fig. 20)}$$

where q is the heat flux and G is mass flow per unit area.

4. Despite the fact that analysts developing the various correlation or mixing length methods have been able to substantiate their work with data, subsequent investigators have usually found it necessary to modify the method to fit their own data. No analysis is currently widely accepted nor has any analysis been thoroughly tested against the available data.

Geometry Effects

1. An increase of about 2:1 in the heat-transfer coefficient on the concave side can be expected as a result of curvature for gases and fluid systems at high T_w/T_b. This enhancement seems to be a centrifuging effect, particularly in small-bend-angle tubes.

2. The magnitude of enhancement (or degradation on the convex side) appears to be related to the Itō parameter. As a reference for computing enhancement for the dry-wall case, correlations of Taylor's type (eq. (9)) appear the most satisfactory. For the wet-wall case, the augmentation can shift to the convex wall.

3. Devices which centrifuge the high-density core to the wall or break up the low-density boundary layer, such as twisted tapes and spiral grooves, enhance near-critical heat transfer significantly.

4. Experiment and analysis suggest that a parallel body force should begin to influence heat transfer when $Gr/Re^2 > 5 \times 10^{-3}$ (where Gr is the Grashoff number and Re is the Reynolds number).

5. Tube entrance effects persist much further down the tube in near-critical fluids than in gases.

Theoretical Considerations in Forced Convection

1. Conventional mixing length theories must be modified to account for the tremendous fluid expansion in the near-critical region. These modifications could be in the equations, following Goldman's example (ref. 137); or in the eddy diffusivity, following Hsu and Smith (ref. 133); or in forming a penetration model, Graham (ref. 150).

2. Applications of these and other modifications of mixing length theory to near-critical data have met with limited success. The theory will probably also have to be

made to comprehend upstream history, acceleration, etc., in order to achieve wide success.

3. Further analysis of accelerated flows should consider the effects of strain rates. While the theory of Deissler predicts the proper trends, the magnitudes associated with a real near-critical fluid are not correct. Thus, the boundaries and the variation in fluid properties must be properly considered (not an easy task).

Oscillations

1. Oscillations in near-critical flow can be divided into four groups: laminar to turbulent, thermal acoustic, system, and external.

2. The large density changes of a near-critical fluid are the basic source of the oscillating behavior.

3. The critical frequency for the thermal-acoustic and system oscillations can be predicted by utilizing simple concepts of mechanics.

4. Conventional stability criteria may be employed to predict the onset of thermal-acoustic and system oscillations with a fair degree of reliability.

5. Attempts to predict the amplitude of the oscillations has met with only limited success.

Choking

1. If a near-critical fluid were in thermodynamic equilibrium, the sonic velocity would be low and the flow might be expected to choke very easily.

2. None of the normal indications of choking have been observed in the near-critical experiments. This suggests the possibility of thermodynamic nonequilibrium in these flows, which is also consistent with two-phase choking experience. Preliminary nozzle data for near-critical nitrogen indicates the expansion to be nonequilibrium.

Zero-Gravity Operation

The operation of a 2.5-liter dewar with internal heaters at supercritical pressure and low gravity was reported as not significantly different from operation for earthbound tests. Data in this area are lacking.

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, June 15, 1970,
            129-01.

APPENDIX A

SYMBOLS

A   constant

Am   amplitude parameter, $PW_n d/Gh_{fg}^*$

A(T)   virial coefficient

A_1 τ_δ/τ_w

A^+ dimensionless parameter of Van Driest (table V)

$\mathscr{A}$ area

a_1 attraction force constant

B(T)   virial coefficient

b_H channel half-width

b_1 repulsion force constant

C   constant

C(T)   virial coefficient

C_p specific heat at constant pressure

$\overline{C_p}$ average specific heat, $(H_w - H_b)/(T_w - T_b)$

$\left(C_p\right)_o$ specific heat at constant pressure, 1 atm

$\left(C_p\right)_r$ excess specific heat, $C_p - \left(C_p\right)_o$

C_v specific heat at constant volume

c   sonic velocity, wave propagation velocity

D   self-diffusion coefficient

D(T)   virial coefficient

D_{ln} binary diffusion coefficient

d   characteristic length (diameter)

d_1 constant

E   Eckert parameter, $(T^* - T_b)/(T_w - T_b)$

E_1, E_2 adjustable constants in analytical equation of state (eqs. (4) and (4a))

F_h	energy (heat) eddy diffusivity modification
F_m	momentum eddy diffusitivy modification
f	function factor
f( )	functional form
$f_1(\rho), f_2(\rho)$	functions describing varations in thermal conductivity and viscosity, respectively
G	mass flow per unit area, $(\rho u)_b$
Gr	Grashoff number: two component, $\rho(\rho_l - \rho)l^3 g/\eta^2$; single component, $\beta_1 \Delta T l^3 g/\eta^2$
g	acceleration
H	enthalpy
h	heat-transfer coefficient
$h(x_1)$	function defined by equation (4a)
h'	modified heat-transfer coefficient, $q_o d^{0.2}/G^{0.8}$
h_{fg}^*	latent heat or pseudolatent heat of vaporization
I	Itō parameter (eq. (27))
L	axial position, length
L_T	one-half total loop length
L'	uniform fluid column length between mixing reservoirs
K	constant
l	characteristic length
l_T	test section length
m	mass
Nu	Nusselt number, hd/λ
n	constant
n_1 to n_{16}	constants in modified BWR equation of state
P	pressure
Pr	Prandtl number, $\eta C_p/\lambda$
p^*	equivalent pressure amplitude when different modes of oscillations occur simultaneously

Q	total heat generated

Q   total heat generated

q   heat flux

R   radius of curvature

Ra   Rayleigh number, $Gr\,Pr$

Re   Reynolds number, $\rho u_b d/\eta$

ℜ   gas constant

r   tube radius

S   entropy

Sr   Stermann parameter (boiling number), $q\,\Delta v/u_b\,\Delta H$

St   Stanton number, $Nu/Re\,Pr$

Sv   specific volume number, v_{fg}^*/v_l

T   temperature

T^* transposed critical or pseudocritical temperature (see fig. 6)

t   dimensionless temperature, $(T - T_c)/T_c$

u   velocity

u^+ dimensionless velocity, u/u^*

u^{++} dimensionless velocity (table V)

u^* friction velocity, $\sqrt{\tau_0/\rho_0}$

V_g volume of gas in resonator cavity

v   specific volume, $1/\rho$

v_{fg}^* change in specific volume, fluid to gas

v'   velocity component normal to flow field

$\overline{v'}$ average velocity component normal to flow field

W   frequency

X   axial position, length

X^+ dimensionless position

x   thermodynamic quality

x_0 adjustable constant in analytical equation of state (eqs. (4) and (4a))

x_1 dimensionless parameter of equation (4), $t\big/\left[(\rho - \rho_c)/\rho_c\right]^{1/\beta_2}$

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y	coordinate normal to flow field
y^+	dimensionless distance, u^*y/ν_O
y^{++}	dimensionless distance (table V)
Z	compressibility factor, $P/\rho \mathcal{R} T$
z	pressure head between heater and cooler
α	void fraction (two-phase system)
β	reference temperature, $q_O u^* \big/ \left(C_p\right)_O \tau_O T_O$
β_1	expansion coefficient
β_2	adjustable constant in analytical equation of state (eqs. (4) and (4a))
γ	ratio of specific heats (isentropic expansion coefficient), C_p/C_v
γ^+	changeover point in equation (42)
$\Delta(\ )$	change in a function
δ	boundary-layer thickness
δ_1	adjustable constant
δ^+	dimensionless boundary-layer thickness, $u^+\delta/\nu_O$
ϵ	momentum eddy diffusivity
ϵ_h	energy (heat) eddy diffusivity
ϵ^+	dimensionless eddy diffusivity, ϵ/ν
ϵ_D^+	dimensionless eddy diffusivity (Deissler form, eq. (42))
ϵ_{VD}^+	dimensionless eddy diffusivity (Van Driest form, eq. (41))
η	viscosity
η^*	viscosity $(\rho \rightarrow 0, T)$
λ	thermal conductivity
λ_f	thermal conductivity given by equation (5)
λ_r	dissociation contribution to thermal conductivity
λ_O^*	thermal conductivity $(\rho \rightarrow 0, T)$
$\mu(\rho, T)$	chemical potential
μ_1	Joule-Thompson coefficient, $\mu_1 = (\partial T/\partial P)_H = 0$

ν	kinematic viscosity, η/ρ
ξ	dimensionless distance, δ/b_H
ρ	density
τ	shear force
$\tau_{contact}$	fluid residence time (eq. (45b))
φ	property parameter (eq. (24))
$\overline{\varphi}$	integral averaged property
χ_{tt}	Martinelli parameter, turbulent-turbulent flow; $\left(\dfrac{1-x}{x}\right)^{0.9}\left(\dfrac{\rho_2}{\rho_1}\right)^{0.5}\left(\dfrac{\eta_1}{\eta_2}\right)^{0.1}$
$(\chi_{tt})'$	modified Martinelli parameter, where x is pseudoquality
$\dot{\omega}$	mass flow rate

Subscripts:

av	average
b	properties evaluated at bulk conditions
c	critical
calc	calculated
core	core of fluid
¢	centerline
cr	curved
cv	concave surface
cx	convex surface
f	properties evaluated at film conditions
fm	properties evaluated at mean film conditions
H	at constant enthalpy
g	gas
l	properties evaluated at liquid conditions
min	properties evaluated according to equation (22a)
n	natural
o	properties evaluated at wall conditions

p	penetration
pg	perfect gas
sat	saturation
st	straight
test	conditions of experimental test
tot	total
w	properties evaluated at wall conditions
x	properties evaluated at reference conditions
δ	edge of boundary layer
$\overline{\varphi}$	properties evaluated at void weighted conditions
0	initial
1	heavy species
2	light species
∞	free stream

1 heavy species ⎫ Do not apply to equations (4), (4a), (5a), and (6a),
2 light species ⎭ where 1 and 2 are ordinary subscripts.

APPENDIX B

HEAT-TRANSFER REGIMES AND THE PROCESS MAP

The heat-transfer problems can be loosely classified into the four regimes, as illustrated in figure 8. However, it is not sufficient just to know what regime is of interest, the process path within these regimes must also be known. For example, a process in region IV (fig. 8) may exhibit very few of the pecularities discussed in the text if the process traverses only a small part of this regime. As a consequence, the designer would have little difficulty in applying a correction to the ordinary Dittus-Boelter equation (ref. 138) and in predicting the heat transfer with reasonable accuracy.

Consider first the problem of establishing the regime of interest, and second the problem of establishing the process path.

In establishing the regime of interest, usually only the thermodynamic limits must be examined (i. e., the operating temperature, the pressure, and the enthalpy (or entropy rise). With these data and a figure similar to figure 8, some decision can be made as to the regime. Such a procedure is flow charted as figure 35. Basically, the message of figure 35 is that if you can avoid operating in the near-critical regime you are better off as far as predicting heat transfer is concerned; however, if you must operate in this regime, the material of this text should be beneficial in delineating problems which must be considered.

In determining the process path assume that a figure similar to figure 8 has been constructed, for example, figure 36. Now examine the five typical process paths illustrated in the figure:

(1) Process path 1: This represents the standard case of a gas entering the apparatus (perhaps with moderate precooling) and exiting as a low-Mach-number gas. The heat-transfer and pressure-drop equations are available and cited herein (see the main text, the section HEAT-TRANSFER REGIONS).

(2) Process path 2: Such a process is closely related to the standard case, except that the working fluid is a liquid at the system inlet and a subcooled liquid at the system exit. This fluid may be at either subcritical or supercritical pressure in a system with low temperature differences - and, of course, there would be no change in phase or pseudophase. Again, standard equations similar to those presented in the main text (see sections HEAT-TRANSFER REGIONS and the NEAR CRITICAL HEAT-TRANSFER REGION) should apply to yield heat transfer and pressure drop.

(3) Process path 3: In such a process, there is a change of phase which complicates the prediction of heat transfer and pressure drop. The process starts as a subcritical, subcooled liquid and terminates in the two-phase regime. While it is difficult to assess
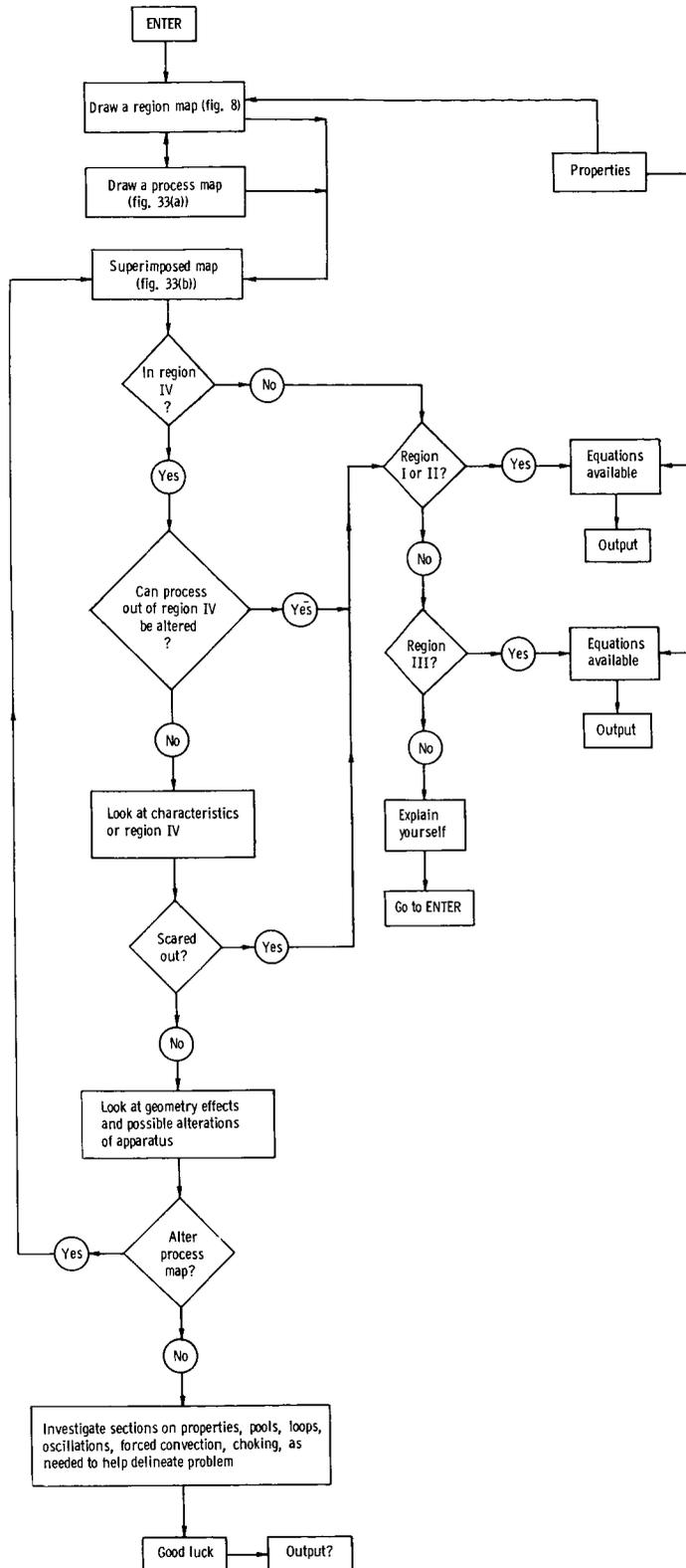
Figure 35. – Flow chart showing procedure of characterizing the heat-transfer process within the four heat-transfer regimes.

Process 1:   Starts and ends as a gas away from critical (sub- or supercritical pressure)
Process 2:   Starts and ends as a liquid away from critical (sub- or supercritical pressure - low ΔT)
Process 3, 3a: Starts liquid or two phase and ends two phase or gas
Process 4: $T_{inlet} < T^* < T_{outlet}$ and high ΔT and high heat fluxes. Usually starts as near-critical liquid

(a) Process path map.   (b) Superposition of process on region map.
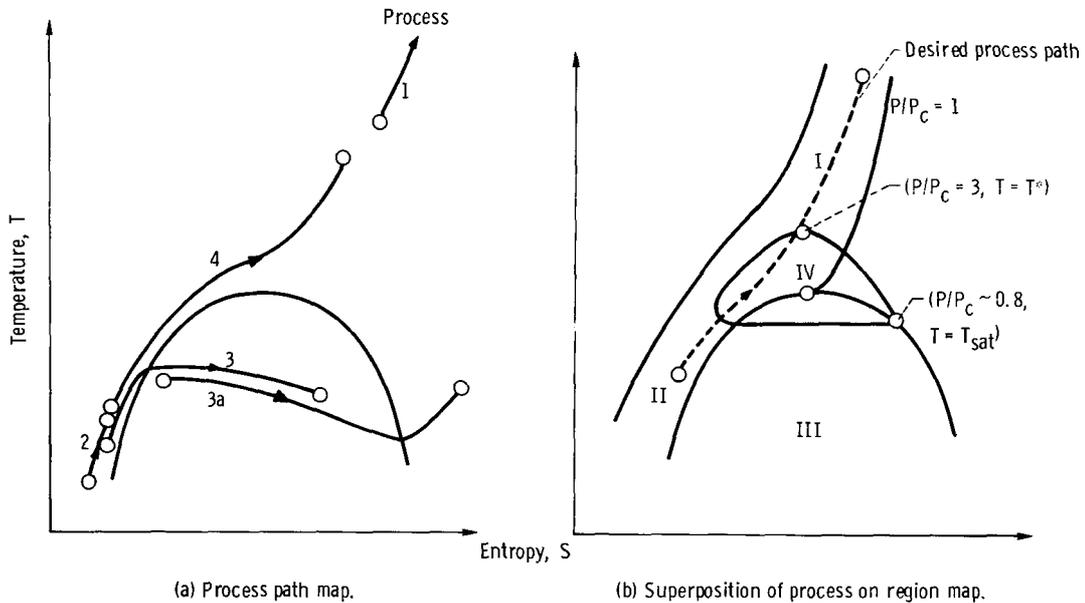
Figure 36. - Typical process paths and characteristic heat-transfer regions.

the region around the saturation locus, several analyses, as discussed in the text, are available which predict heat transfer and pressure drop with reasonable accuracy.

(4) Process path 3a: Such a process enters the system as a two-phase fluid; however, the exhausted fluid is gaseous or perhaps droplet-laden. This is a difficult regime to assess; however, the techniques of Hsu, et al. (ref. 49) should be applicable.

(5) Process path 4: These are the systems operating in the near-critical regime, where, as a general rule, heat-transfer predictions are poor. However, if the boundaries of region IV are not crossed (see fig. 36), it appears to be possible to make a reasonable prediction. If in the final analysis, the process crosses the boundaries, the problem will be a real challenge. Some of the problems involved in analyzing such a system are covered in the main text of this report.

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