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ANALYSIS OF THREE LIQUID-METAL QUALITY MEASUREMENT TECHNIQUES

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SUMMARY

Three techniques were theoretically evaluated to determine potential accuracy and design problem areas. The techniques considered were calorimetric, flow measurement, and acoustic techniques. Calorimetric techniques had root-sum-square errors ranging from 0.0028 to 0.015 for heating and condensing calorimeters, to 0.0027 for throttling calorimeters. These estimates were based on applying systematic corrections for heat losses and did not include sampling errors. Sampling errors may approach 0.01 or more. Two-phase flow measurement techniques have potential root-sum-square errors of 0.014 in a small range of weight flows around the design point. Problems associated with achieving thermodynamic equilibrium during the passage of an acoustic pulse in a two-phase fluid apparently limit the application of sonic velocity measurement techniques.

INTRODUCTION

Measuring the relative composition of two-phase fluids is a problem that has challenged instrument designers for years. This problem has been encountered in a wide variety of technologies and has resulted in measuring techniques suitable for environments from steam power systems to cryogenic flow lines (refs. 1 to 9). One of the most difficult environments yet encountered is that of Rankine-cycle space power systems. In this case the fluids are alkali metals, most commonly potassium and sodium, and the temperatures range from 1500° to 2200° F. The literature cites few cases in which the quality or liquid-vapor content of such fluid streams is measured. An exception is reference 10, in which measurements with a throttling calorimeter are reported. However, details on the instrument design and estimated accuracy are not included. Instrument design and error analyses of quality measurement techniques are reported in references 11 and 12. More commonly, liquid-vapor content is estimated from overall heat-balance calculations, a procedure limited in accuracy by extraneous heat losses.

Quality measurement is vital to the Rankine-cycle space-power-system program because it defines the energy content of the two-phase fluid. Space-power-system studies (ref. 13) indicate that operation with turbine-inlet vapor of very high quality to a slightly superheated state is required to achieve a minimum system specific weight. For system testing with wet vapor, quality measurements are required to determine the turbine-inlet conditions and to monitor boiler performance. Quality measurement is also an aid in boiler development work because it provides a measure of boiler performance.

A quality meter is not sufficient to fill all the needs for two-phase instrumentation. Instrumentation to define flow regimes (i. e., bubbly, slug, annular, or mist flow) and void fraction (percentage vapor by volume) is required in studies of the boiling and condensing processes. Also, instrumentation to detect liquid droplets in vapor streams and to measure droplet sizes and velocities is of interest, especially in turbine-blade-erosion studies. Quality measurement does, however, provide a most basic need in two-phase instrumentation, which is energy-content measurement.

This report analyzes three measuring techniques that are applicable to the measurement of quality in alkali-metal two-phase streams, (1) calorimetric, (2) weight-flow measurement, and (3) sonic velocity or acoustic techniques. Quality is the ratio of the weight flow of vapor to the total weight flow of the stream. One prime prerequisite for a liquid-metal-quality measuring system is that it be inherently capable of measurement without the need for calibration. Each technique is analyzed from the standpoint of the fundamental principles involved, the physical measurements required, and the practical problems of applying the technique to two-phase alkali-metal systems.

For the calorimetric and two-phase weight-flow techniques, error equations are developed, and estimated probable errors are calculated. For the sonic velocity technique, the basic assumptions required for quality determination are examined in relation to the properties of the fluid stream. In this examination, work of a similar nature with two-phase hydrogen (ref. 14) is used.

SYMBOLS

A	area
a	thermal expansion coefficient
B	constant, 1.26
C	sonic velocity
c_p	specific heat

D	droplet diameter
d	pipe diameter
f	frequency, Hz
g	gravitational constant
h	enthalpy
h_{fg}	heat of vaporization
J	mechanical equivalent of heat
K	flow coefficient
k	thermal conductance
L	error producing variable
M	$\frac{K_g Y_g A}{w} \sqrt{\frac{2Gp}{v_g}}$
N	$\frac{BK_g Y_g}{K_f} \sqrt{\frac{v_f}{v_g}}$
P	absolute pressure
p	pressure difference
Q	energy added
q	energy loss
R	r_f/r_g
r	radius
T	temperature
T_o	calibration temperature
V	velocity
V_s	free-stream velocity
v	specific volume
w	weight-flow rate
ΔX	sampling error
x	quality

x_s	free-stream quality
Y	expansion factor
y	moisture content, 1 - x
α	thermal diffusivity, $k/\rho c_p$
β	orifice-pipe diameter ratio
μ	fluid viscosity
ν	kinematic viscosity
ρ	density
τ	time constant
ω	frequency, rad/sec

Subscripts:

f	saturated liquid or droplet
g	saturated vapor
is	isentropic
o	near measurement point or orifice
x	mixture
1, 2, 3	measurement locations

PRELIMINARY CONSIDERATIONS

Description of Fluid

In the quality range of interest, 0.85 to 1.0, the fluid can be described as a mist; on a volumetric basis, it is mostly vapor with the liquid phase dispersed in the form of small droplets. The droplet diameters are estimated to range between 1 and 100 microns at concentrations between 10^2 and 10^8 droplets per cubic centimeter, depending on the method of vapor generation, phase densities, stream quality, and stream turbulence. For typical potassium and sodium systems, the Reynolds numbers range from 10^4 upward, which indicates turbulent flow conditions. Because of the high droplet concentration and turbulent flow conditions, the fluid is considered to be a continuous and homogeneous mixture of the two phases.

Evaluation of Thermodynamic Properties

In the measurement of quality, thermodynamic properties must be used. The literature reveals a number of sources for property data. A comparison of data (ref. 15), however, indicates that significant differences exist among the property values given in various sources. As an example, an 8-percent variation in values for the heat of vaporization of potassium at 1800° F can be calculated from figure 13 of reference 15. These differences result in systematic uncertainties in the measurement. They will not enter into the random error calculations presented for the calorimetric and flow measurement techniques. In the section, Effects of property variation on quality computations, the difference in quality values resulting from the use of two tables of thermodynamic properties is given.

Thermodynamic properties for use in quality determinations are obtained from tables or curves with the use of the primary measurements of temperature and/or pressure as indices. The accuracy by which the properties can be found is a function of the accuracy involved in the primary measurement and may be determined by standard error analysis methods. To evaluate the uncertainty in a property requires knowledge of the partial derivative of the property with respect to temperature and to pressure and estimates for the errors in these measurements. The partial derivatives are computed on a finite difference basis from property tables. The choice of a particular table is not critical since reference 15 shows these partial derivatives to be similar in the temperature range of interest.

The errors in temperature and pressure measurements are considered random. The probable error of an absolute pressure measurement in liquid metals is estimated at ±1 percent of full scale or ±0.1 pound per square inch, whichever is larger. The assumed probable error in a temperature measurement is ±3/8 percent of the reading. These estimates are considered optimistic but are useful in establishing the potential value of the techniques considered.

A summary of the uncertainty in the saturated thermodynamic properties of potassium at 1600° and 2200° F is given in table I. The computations were based on data from reference 16. The properties are shown in two columns depending on whether the temperature or the pressure was the measured variable. Note that the largest uncertainty involves the determination of the specific volume of the saturated vapor.

TABLE I. - ERROR IN PROPERTY EVALUATION FOR POTASSIUM

[$\Delta P/P$, 0.01; $\Delta T/T$, 0.00375.]

Error producing variable, L	Saturation temperature, °F			
	1600		2200	
	Error, percent			
	$\frac{1}{L}\frac{\partial L}{\partial P}\Delta P$	$\frac{1}{L}\frac{\partial L}{\partial T}\Delta T$	$\frac{1}{L}\frac{\partial L}{\partial P}\Delta P$	$\frac{1}{L}\frac{\partial L}{\partial T}\Delta T$
Specific volume				
Liquid, v_f	0.053	0.13	0.10	0.21
Vapor, v_g	.83	2.2	.87	1.8
Enthalpy				
Liquid, h_f	0.11	0.30	0.17	0.35
Vapor, h_g	.088	.021	.018	.036
Heat of vaporization, h_v	0.045	0.12	0.093	0.19

ANALYSIS OF MEASUREMENT TECHNIQUES

Calorimetry

Calorimetric quality measurement techniques utilize a steady-flow process in which the two-phase fluid is either heated, condensed, or expanded. The process continues until a single-phase fluid of measurable energy content is achieved. By measuring the amount of energy required to achieve the final state, the initial energy content and therefore quality of the two-phase fluid is determined.

A schematic diagram of a calorimetric system is shown in figure 1. The system consists of a sampling probe, a process chamber, and a flowmeter. The fluid enters the system at station 1, where a temperature or pressure measurement establishes the initial saturated state. Energy is removed or added, or the fluid is expanded until a single-phase fluid is achieved at station 2. The weight flow rate of the fluid is then measured. The steady-flow energy equation for the process, with gravitational effects neglected, is

$$\frac{V_1^2}{2Jg} + h_1 + \frac{Q}{w} = \frac{V_2^2}{2Jg} + h_2 + \frac{q}{w} \tag{1}$$

The enthalpy h_1 is related to quality by

$$h_1 = h_{g,1} - (1 - x)h_{fg,1} \tag{2}$$

Combining equations (1) and (2) and neglecting the kinetic energy terms result in the following expression for quality:

$$x = 1 - \frac{h_{g,1} - h_2}{h_{fg,1}} - \frac{Q}{wh_{fg,1}} + \frac{q}{wh_{fg,1}} \tag{3}$$

For systems in which the velocities are in the range of 100 feet per second or less, the kinetic energy term is small in comparison with the other terms and can be neglected. If stream velocities are much higher or uncertain in magnitude, they must be considered in an error analysis.

Equation (3) includes two energy terms. The first term $Q/wh_{fg,1}$ represents the measured amount of energy required to achieve a single-phase fluid at station 2. In this derivation, the term is positive for heating, negative for condensing, and zero for throttling calorimeters. The second term $q/wh_{fg,1}$ considers heat losses from the process chamber that are functions of system design and environmental operating conditions. The actual value for the heat loss may be determined experimentally and a systematic correction applied to the measurement. This term is treated as a constant in the error equations.

The root-sum-square error as discussed in this report is defined by the following expression:

$$\Delta x^2 = \sum_{i=1}^{n} \left(\frac{\alpha x}{\alpha L_i}\right)^2 \Delta L_i^2 \tag{4}$$

Simplified expressions for the root-sum-square error in each of the calorimetric systems can be obtained by making use of the following assumptions and approximations:

(1) Negligible superheating or subcooling occurs in the process chamber. This assumption implies that $(h_{g,1} - h_2)/h_{fg,1}$ is 0.0 for a heating calorimeter and is 1.0 for a condensing calorimeter.

(2) The following approximations are made:

$$\frac{dh_{g,1}}{h_{g,1}} = \frac{dh_2}{h_2} = \frac{dh_{fg,1}}{h_{fg,1}}$$

(3) The heat loss correction $q/wh_{fg,1}$ is assumed to be 0.01 with error of ±10 percent, and is assumed to be constant.

Using the values for potassium at 2200° F from reference 17 produces the following error equations:

Heating calorimeter:

$$\Delta x = \left\{\left[6.2 + (1.01 - x)^2\right]\left(\frac{\Delta h_{fg,1}}{h_{fg,1}}\right)^2 + 10^{-4}\left[\frac{\Delta\left(\frac{q}{wh_{fg,1}}\right)}{\left(\frac{q}{wh_{fg,1}}\right)}\right]^2 + (1.01 - x)^2\left[\left(\frac{\Delta w}{w}\right)^2 + \left(\frac{\Delta Q}{Q}\right)^2\right]\right\}^{1/2} \tag{5a}$$

Condensing calorimeter:

$$\Delta x = \left\{\left[3.7 + (1.01 - x)^2\right]\left(\frac{\Delta h_{fg,1}}{h_{fg,1}}\right)^2 + 10^{-4}\left[\frac{\Delta\left(\frac{q}{wh_{fg,1}}\right)}{\left(\frac{q}{wh_{fg,1}}\right)}\right]^2 + (0.01 - x)^2\left[\left(\frac{\Delta w}{w}\right)^2 + \left(\frac{\Delta Q}{Q}\right)^2\right]\right\}^{1/2} \tag{5b}$$

Throttling calorimeter:

$$\Delta x = \left\{\left[6.2 + (1.01 - x)^2\right]\left(\frac{\Delta h_{fg,1}}{h_{fg,1}}\right)^2 + 10^{-4}\left[\frac{\Delta\left(\frac{q}{wh_{fg,1}}\right)}{\left(\frac{q}{wh_{fg,1}}\right)}\right]^2\right\}^{1/2} \tag{5c}$$

In the following paragraphs, various physical configurations of the calorimeters are described. Based on these configurations, estimates for the error terms in equations (5) are made. Also described are some of the operational characteristics peculiar to each calorimeter.

Heating and condensing calorimeters. - For the heating calorimeter, the most convenient source of energy input to the process chamber is an electric heater. The probable error in measuring the heat input is 1/2 percent. A condensing calorimeter requires a heat exchanger in which the actual energy measurement is probably made on a second fluid. The probable error of such an energy measurement is estimated at 1 percent. Most calorimeters operate with flow rates in the range of 20 pounds per hour. For this range, thermal flowmeters are practical, with a root-sum-square error of $1\frac{1}{4}$ percent. Some design and operating problems for thermal flowmeters include minimizing heat losses and measuring the fluid bulk temperature.

For a condensing calorimeter, a volumetric flowmeter might also be considered. This device involves the measurement of a time interval required to fill a known volume with liquid. The uncertainty in such a measurement system would be comparable to that achieved in the thermal devices. The magnetic flowmeter does not appear applicable to this problem because of the small flow rates involved.

The principle of a calorimeter involves achieving a single-phase fluid at the outlet. Thus, ideally, the energy content is directly measurable. In a heating calorimeter, however, liquid carryover may occur; thus, some uncertainty is introduced in the state of the fluid. The extent of this problem depends on initial droplet size, fluid turbulence, surface-tension effects, and the amount of droplet coalescence. In contrast, the condensing calorimeter should be capable of operating such that only liquid is present at the outlet, and therefore, the question of phase composition is not involved.

Throttling calorimeter. - The throttling calorimeter utilizes a steady-flow adiabatic expansion process in which no work is done on or by the fluid. Consequently, the only error involved in this device is that caused by determining enthalpies. A discussion of throttling-calorimeter feasibility is given in reference 12. The report indicates that the throttling calorimeter is limited from considerations of thermodynamics to measurements in the 0.91 to 1.00 quality range for potassium. The limitation is based on inlet temperatures between 1600° and 2200° F and on expansion pressures of 1 to 10 pounds per square inch absolute in the process chamber.

From equation (5c), the uncertainty in a measurement of quality approaches 0.0025 with a throttling calorimeter based on $\Delta h_{fg,1}/h_{fg,1} = 0.001$. (A limit of error was estimated at 0.01 in ref. 12, as opposed to the root-sum-square error used in this report.) Because of the simplicity of a throttling calorimeter and from a more thorough heat-transfer analysis, the heat loss error was estimated at 0.005 in reference 12 and was not included as a correction in the measurement.

Summary of errors in calorimeters. - A summary of the root-sum-square errors for calorimeters is given in table II. Indicated are the assumed values of error for the latent heat, weight-flow, and energy measurements. Under these conditions, less error is involved in using throttling and heating calorimeters than in using condensing calorimeters. For covering a wide range of qualities, the use of a heating calorimeter should be considered.

TABLE II. - ROOT-SUM-SQUARE ERROR IN CALORIMETERS

Calorimeter	Error term					Quality	
	$\frac{\Delta h_{fg}}{h_{fg}}$	$\frac{\Delta w}{w}$	$\frac{\Delta Q}{Q}$	$\frac{q}{wh_{fg}}$	$\frac{\Delta q/wh_{fg}}{q/wh_{fg}}$	0.85	0.95
						Root-sum-square error	
Heating	0.001	0.0125	0.005	0.01	0.10	0.0034	0.0028
Condensing	.001	.0125	.01	.01	.10	.014	.015
Throttling	.001	------	-----	.01	.10	------	.0027

Sampling error. - Obtaining a representative sample of a two-phase fluid is a problem and is an important prerequisite for achieving reliable calorimetric quality measurements. Even when the liquid and vapor phases are homogeneously dispersed in the flow line, as assumed herein, an error caused by sampling can arise. This error results from the difference in momentum of the liquid drop and the vapor. A number of reports are available (refs. 7, 9, and 12) that recommend methods for minimizing sampling error. One basic recommendation is that the probe and flow system be designed to ensure that the velocity at the probe inlet is equal to that of the free stream at the measurement plane. In reference 12, the effects of velocity differences on sampling error are discussed, and the following equation is derived, which relates sampling error to the velocity ratio and quality:

$$\Delta x = x_s - \frac{1}{1 + \left(\frac{1 - x_s}{x_s}\right)\overline{V}}$$

where

$$\overline{V} = \frac{V_s}{V_1}$$

For an allowable sampling error, the required degree of control and knowledge of the velocities can be obtained by solving the equation for $\overline{V}$.

$$\overline{V} = \left(\frac{x_s}{1 - x_s}\right)\left(\frac{1}{x_s - \Delta x} - 1\right) \tag{6}$$

As an example, if the allowable sampling error were 0.01, the velocity at the inlet V_1 must be controlled to within 20 percent of V_s when measuring qualities in the 0.95 range. However, for measurements in the 0.85 range, the control must be to within 8 percent. Thus, to minimize the sampling error in the lower quality range, precise control of free-stream and sampling-probe velocities is required. In many liquid-metal applications it is difficult to control the velocities to the required degree, and, therefore, an analysis of other measurement techniques that do not necessarily require sampling was undertaken.

Flow Measurement

In reference 18, Murdock derives an equation relating the total weight flow of a two-phase fluid passing through a sharp-edged orifice to the measured pressure drop, the moisture content, and fluid metering constants. This equation was developed from a rational approach to two-phase flow measurements and contains an empirical constant determined from correlating many two-phase flow measurements. The equation was developed for use in steam-water flows in large power plants and for metering in natural gas piping systems. Since the moisture content is equal to $1 - x$, this metering system, in conjunction with a second measurement of total weight flow, could determine quality. The potential advantages of this method are that measurement of the entire fluid flowing in a pipe eliminates sampling and that absence of heat losses eliminates a source of correction required for calorimetric devices. Thus, the evaluation in some detail of the applicability of this flow-measurement technique for liquid-metal quality determination is of interest.

The total weight-flow rate of a two-phase fluid passing through a sharp-edged orifice is found from the following equation developed in reference 18:

$$w = \frac{K_g Y_g A\left(\dfrac{2Gp}{v_g}\right)^{1/2}}{1 - y + By\dfrac{K_g Y_g}{K_f}\left(\dfrac{v_f}{v_g}\right)^{1/2}} \tag{7}$$

where

$$y = 1 - x$$

$$B = 1.26\text{(constant)}$$

This equation is applicable to meters designed, constructed, and installed in accordance with ASME standards. Solving the equation for quality results in

$$x = \frac{\dfrac{K_g Y_g A}{w}\left(\dfrac{2Gp}{v_g}\right)^{1/2} - \dfrac{BK_g Y_g}{K_f}\left(\dfrac{v_f}{v_g}\right)^{1/2}}{1 - \dfrac{BK_g Y_g}{K_f}\left(\dfrac{v_f}{v_g}\right)^{1/2}} \tag{8}$$

The constants in equation (8) include flow coefficients, the orifice area, and an expansion factor. In fluid metering, the flow coefficients are determined with the use of a Reynolds number correlation. For liquid-metal applications, both air and water may be used to obtain the necessary Reynolds number range for determining the constants K_g and K_f. The fluid expansion factor takes into account the compressibility of the fluid and is obtained from tables by using the ratios of specific heats and measured pressures as indices.

Error evaluation for two-phase flowmeter technique. - For the purposes of this section, all sources of error in the measurement of quality with a flowmeter are considered as random errors. The total error in the measurement is then taken as the root sum square of the individual errors (eq. (4)), which can be written as

$$\frac{\Delta x}{x} = \left\{ \left(\frac{1}{1 - N}\right)^2 \left[\left(\frac{\Delta K_g}{K_g}\right)^2 + \left(\frac{\Delta Y_g}{Y_g}\right)^2 + \left(\frac{1}{2}\frac{\Delta v_g}{v_g}\right)^2\right] + \left[\frac{M}{x(1 - N)}\right]^2 \left[\left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta w}{w}\right)^2 + \left(\frac{1}{2}\frac{\Delta p}{p}\right)^2\right] \right.$$

$$\left. + \left[\frac{(x - 1)N}{x(1 - N)}\right]^2 \left[\left(\frac{\Delta B}{B}\right)^2 + \left(\frac{\Delta K_f}{K_f}\right)^2 + \left(\frac{1}{2}\frac{\Delta v_f}{v_f}\right)^2\right] \right\}^{1/2} \qquad (9)$$

where

$$M = \frac{K_g Y_g A}{w}\left(\frac{2Gp}{v_g}\right)^{1/2}$$

$$N = B \frac{K_g}{K_f} Y_g \left(\frac{v_f}{v_g}\right)^{1/2}$$

The error terms are evaluated in appendix A. A summary of the terms is as follows:

$$\frac{\Delta K_g}{K_g} = 2.1\times10^{-3}$$

$$\frac{\Delta Y_g}{g} = 4\times10^{-3}$$

$$\frac{1}{2}\left(\frac{\Delta v_g}{v_g}\right) = 5\times10^{-3}$$

$$\frac{\Delta A}{A} = 2.5\times10^{-3}$$

$$\frac{\Delta w}{w} = 10\times10^{-3}$$

$$\frac{1}{2}\left(\frac{\Delta p}{p}\right) = 5\times10^{-3}$$

$$\frac{\Delta B}{B} = 5\times10^{-3}$$

$$\frac{\Delta K_f}{K_f} = 2.1\times10^{-3}$$

$$\frac{1}{2}\left(\frac{\Delta v_f}{v_f}\right) = 5\times10^{-3}$$

Basing the values of M and N on the specific volumes for saturated potassium at 1600° F (ref. 16) and assuming that $Y_g = 0.97$, $K_g = K_f$, and $x = 0.90$ produces representative values for M and N of 0.90 and 0.052, respectively. Thus, the root-sum-square error as given by equation (9) is 0.014 for the flow measurement technique. This error would be equivalent to that computed for either the throttling or heating calorimeter when sampling errors (0.01) are considered in these measurements.

Differential pressure measurement. - The differential pressure measurement is the primary measurement required when the flow measurement technique is used. A general indication of the differential pressure range can be obtained by considering the pressure drop developed in a sharp-edged orifice through which a saturated liquid-metal vapor is flowing. Figure 2 shows the pressure difference p as a function of fluid velocity with the orifice coefficient assumed to be 0.6. Lines are shown for potassium at temperatures of 1600° and 2200° F. For practical meter systems, the throat velocities would be about 500 feet per second, which corresponds to differential pressures between 6 and 30 pounds per square inch. For a two-phase fluid, the differential pressure is somewhat higher because it is approximately inversely proportional to quality for a given fluid velocity.

The measurement of low pressures in liquid-metal systems is difficult. Fortunately, there are a few methods, such as inert gas bleed systems, which are capable of achieving differential pressure measurements (refs. 19 and 20) accurate to within ±0.1 pound per square inch. Also, commercial high-temperature differential pressure transducers are available, and if care is used in their installation and operation, accuracies approaching 1 percent of the reading (as estimated in the error analysis) are obtainable. Flowmeter systems such as these have one limitation; namely, a given system is capable of making accurate measurements only over a small range of weight flow rates around the design point. This limitation occurs because the weight flow rate is proportional to the square root of the pressure difference p. Consequently, for a given uncertainty in p, the error becomes large at flow rates less than the design point. Examination of equation (8) and the coefficients M and N leads to a similar conclusion for the measurement of quality. This particular characteristic may be a deciding factor in the choice of the flowmeter technique for quality measurements.

Effects of property variation on quality computations. - A comparison of the effects of differences in thermodynamic property data on the computed values of quality for the calorimetric and flow measurement techniques is now made. In appendix B are derived equations (B1), (B2), (B3), and (B5), which relate the difference between the values of quality computed from the data of reference 16 and 21 to inlet saturation temperature. The derivations were based on the assumption of no superheat or subcooling at the outlet. Also, use was made of linearized relations between the saturation properties and temperature. From the equations, the following conclusions are reached: For the two sets of property data used, the difference in computed values of quality for the heating calorimeter approaches 6 percent of the moisture present in the stream while that for the condensing calorimeter approaches 6 percent of the measured value of quality. For the throttling calorimeter, the differences approach one-half the amount of moisture present in the stream while the difference for the flowmeter system ranges between ±3 percent of the measured value of quality.

Sound Velocity

The sonic velocity in a two-phase fluid is theoretically a function of fluid quality. The measurement of sound velocity, therefore, might be used as the basis for a quality-measuring system. Such a system would consist of a sound generator and an acoustic transducer located a known distance from the generator. The advantages of this system include freedom from sampling errors and heat loss corrections, provided that the required instrumentation can be located in the stream. In the following sections, an analysis of the thermodynamic process is given along with a discussion of the heat transfer and mechanics of the vapor and droplet interaction.

Process equation. - The thermodynamic equation relating sonic velocity to fluid properties for any fluid is

$$C^2 = \left(\frac{\partial P}{\partial \rho}\right)_{is} \tag{10}$$

TABLE III. - SONIC VELOCITY OF POTASSIUM

Temperature, $^{\circ}F$	Quality, x				
	0.85	0.90	0.95	0.98	0.99
	Sonic velocity, ft/sec				
1600	1558	1606	1653	1681	1690
1700	1586	1636	1684	1713	1722
1800	1612	1663	1713	1742	1751
1900	1635	1688	1739	1769	1778
2000	1657	1710	1763	1793	1803

where

$$\left(\frac{\partial P}{\partial \rho}\right)_{is} = f(x)$$

Papers have been published giving the sonic velocity as a function of quality and temperature (e.g., refs. 1 and 14) for many fluids. Table III gives values for the sonic velocity of potassium that were computed on a finite difference basis with the use of equation (10) and the equations of state as given in reference 17. The table indicates that the sonic velocity changes approximately 10 feet per second for a 0.01 change in quality. If the sonic velocity can be measured to within 1/2 percent, the resulting error is approximately 0.008 in quality. Also, this table shows that the effects of temperature on the sonic velocity are not great, with a change of 30 feet per second for a 100° F change in temperature. With a probable error of ±3/8 percent for temperature measurements, an additional uncertainty of 0.0018 (at 1600° F) is introduced into the measurement. The resulting root-sum-square error is 0.008.

When use is made of equation (10), the fluid must be in thermodynamic equilibrium during the passage of the acoustic wave. To maintain equilibrium, both phases must be at the same temperature and move as a unit at all times. Since it is obvious that these conditions cannot be achieved over wide ranges of acoustic frequencies, it is of interest to examine the mechanical and thermal aspects of this problem.

Heat-transfer considerations. - Consider a mixture in which both phases of the fluid are at the same saturated conditions. On a typical temperature-entropy diagram (fig. 3) the mixture is assumed to exist at state point 1. The propagation of an acoustic pulse will result in a compression and a rarefaction of the fluid. For the isentropic compression process, state point 2 may be achieved. This process results in a change in the quality of the mixture and, therefore, in mass and heat transfer between phases.

Since energy cannot be transferred instantaneously, a relaxation time is involved in the process. For the purposes of establishing the relaxation time, the mixture is assumed to consist of a number of spheres equal to the number of droplets present. Each sphere consists of a liquid droplet surrounded by a vapor shell. The volume of the shell is so proportioned that the quality of a given sphere is the same as that of the mixture. To simplify the problem further, it is assumed that no heat is transferred between the various spheres. The relaxation times or time constants for the process of interest are those which are characteristic of the temperature distribution in a droplet or shell when a step change in the interface temperature occurs. The equations for these time con-

TABLE IV. - RELAXATION TIME CONSTANTS FOR POTASSIUM AT 2200° F

Quality, x	Droplet diameter, μm			
	2	10	50	100
	Time constant of vapor shells, τ_g, sec			
0.80	2×10^{-5}	5×10^{-4}	1×10^{-2}	5×10^{-2}
.90	4×10^{-5}	1×10^{-3}	3×10^{-2}	1×10^{-1}
.95	1×10^{-4}	2×10^{-3}	6×10^{-2}	2×10^{-1}
.99	5×10^{-4}	1×10^{-2}	3×10^{-1}	1.2×10^{0}
	Time constant of liquid drops, τ, sec			
----	2×10^{-9}	6×10^{-8}	2×10^{-6}	6×10^{-6}

stants are taken from reference 14. For a sphere, the relaxation time constant is found from

$$\tau_f = \frac{r_f^2}{\alpha_f \pi^2} \tag{11}$$

The relaxation time constant for a spherical shell is

$$\tau_g = \frac{r_f^2\left(R^{-2} - 1\right)}{\alpha_g \delta^2} \tag{12}$$

where R is the ratio of the droplet radius to sphere radius and is related to quality and phase density by

$$R = \left[\frac{1}{1 + \left(\frac{x}{1 - x}\right)\left(\frac{\rho_f}{\rho_g}\right)}\right]^{1/3}$$

(Eq. 3.5 in ref. 14 differs somewhat from this equation.) The angle δ is found from the following transcendental equation:

$$\frac{\delta}{\tan \delta} = 1 - R$$

Relaxation time constants for potassium at 2200° F are given in table IV. The table indicates that the time constants for the size of droplets expected in liquid-metal systems are very short, less than 10^{-5} second. On the other hand, the time constants for the vapor shells approach seconds. Because of these long time constants, slow pressurization rates and, therefore, low acoustic frequencies will be required to maintain equilibrium. Note that the foregoing calculations do not include the heat required to effect a change in quality; thus, the actual time constants would be longer.

Mechanical considerations. - A second limitation on the operating frequency of an acoustic system results from the requirement that the vapor and droplets move as a unit. In reference 14, general equations are given for the passage of an acoustic wave in a fluid containing particles and vapor. These equations were derived by considering the viscous forces acting on the particles and their resulting motion as a function of the vapor motion. It was assumed that the vapor and droplets move in a sinusoidal manner and that the movement of the droplet lags that of the vapor by some phase angle ϵ. The following equation from reference 14 gives the ratio of the droplet velocity to that of the vapor. The droplets were assumed to be rigid spheres.

$$\frac{V_g - V_f}{V_g} = \frac{1 - \frac{\rho_g}{\rho_f}}{\left[\theta^2 + (1 + \Phi)^2\right]^{1/2}} \tag{13}$$

where

$$\Phi = \left(\frac{1}{2} + \frac{9}{4\beta r_f}\right)\frac{\rho_g}{\rho_f}$$

$$\theta = \frac{9}{4}\frac{1}{\beta r_f}\left(1 + \frac{1}{\beta r_f}\right)\frac{\rho_g}{\rho_f}$$

$$\beta = \left(\frac{\omega}{2\nu_g}\right)^{1/2}$$

$$\epsilon = \tan^{-1}\frac{\theta}{\Phi + 1}$$

Values for the velocity ratio are shown in figure 4 as a function of a diameter-frequency parameter fD^2 for potassium at 1600° and 2200° F, where $(\beta r_f)^2 = \pi f D^2/4\nu_g$. These curves show that the droplets will move with the vapor for values of $fD^2 < 10^4$. Thus, for a 50-micron droplet, the system must operate at 4 hertz or less to minimize the relative velocity. This operating frequency also approaches that necessary for maintaining temperature equilibrium as previously discussed.

The effect of relative velocity between the vapor and liquid droplets on the sonic velocity of the fluid is shown in figure 5. The curves were computed from an equation which is a solution to the wave equation for a pressure pulse transmitted through a vapor in which are dispersed many particles. The equation is derived in reference 14 and is as follows:

$$\frac{C_x}{C_g} = \left\{1 + \left(\frac{1 - x}{x}\right)\left[\frac{\Phi(1 + \Phi) + \theta^2}{(1 + \Phi)^2 + \theta^2}\right]\left[1 - \frac{\rho_g}{\rho_f}\right]\right\}^{-1/2} \tag{14}$$

For $fD^2 < 10^4$, the sound velocity is constant and a function of the mixture quality. As fD^2 increases, the presence of the droplets affects the sound velocity to a lesser degree.

This examination of the heat transfer and mechanics of the phase interaction indicate that the use of a sound velocity measurement for quality determination requires operating at a value of the diameter-frequency parameter less than 10^4. In the section, Description of Fluid, the droplet diameters were estimated to be between 1 and 100 microns. Covering this range of diameters and maintaining a diameter-frequency parameter value of 10^4 would require measuring frequencies approaching 1 hertz. In practice, liquid-metal systems often exhibit pressure fluctuations at these low frequencies. Therefore, signal to noise ratio problems would be encountered, which introduce uncertainty in a measurement. Since quality measurement techniques cannot be calibrated to overcome such problems, the sonic velocity measurement technique does not appear practical. However, in determining the presence of small droplets, the technique may be of some use since higher operating frequencies may be utilized and the signal to noise ratio thereby maximized.

CONCLUSIONS

In an analysis of three liquid-metal quality measurement techniques, the use of calorimetry was concluded to be the most practical method available at this time. On the basis of applying a systematic heat loss correction, estimated root-sum-square errors for these devices were 0.015 for a condensing calorimeter, 0.0028 for heating calorimeters, and 0.0027 for throttling calorimeters. The major source of error in these devices resulted from errors in the weight flow measurement. Also, sampling of the two-phase stream presents a problem when using calorimetric methods with sampling errors approaching 0.01.

Two-phase flow measurement techniques have a potential root-sum-square error of 0.014. The measurement of the small differential pressures is a problem in the use of this technique. The technique is limited to measurements near design conditions because of the functional relation between quality and differential pressure.

The use of a sonic velocity measurement technique does not appear practical at this time. The main problem is associated with achieving thermodynamic equilibrium during the passage of a pressure wave. Because of the required diameter-frequency parameter range for achieving equilibrium, the environmental conditions, and uncertainty in droplet sizes, this technique is limited in application.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 20, 1967,
120-27-02-04-22.

APPENDIX A

FLOWMETER ERROR TERM EVALUATION

Flow Coefficient

The flow coefficients $\Delta K_g/K_g$ and $\Delta K_f/K_f$ are a function of Reynolds number and are usually obtained from a calibration with air or water used as the working fluids. The accuracy of a calibration is in the 1/8 percent range. The total error in knowledge of the flow coefficient is found in the following manner: Assume that the functional relation exists such that

$$K_g = K_{g,o} + f(Re)$$

where Re is the Reynolds number. Let $K_{g,o} >> f(Re)$. Then

$$\frac{\Delta K_g}{K_g} = \left[\left(\frac{\Delta K_{g,o}}{K_{g,o}}\right)^2 + \left(\frac{1}{K_{g,o}} \frac{\partial f}{\partial Re} \Delta Re\right)^2\right]^{1/2} \qquad \text{(A1)}$$

The first term in equation (A1) is taken as the calibration error:

$$\frac{\Delta K_{g,o}}{K_{g,o}} = 0.00125$$

The partial derivative in equation (A1) will be evaluated on a finite difference basis from tables in reference 22. The sharp-edged orifice under consideration will be for a 2-inch pipe with flange taps, Reynolds number of 10 000, and an orifice-pipe diameter ratio β of 0.25. For this configuration $K_{g,o} = 0.61$, and from table 6 of reference 22, the partial derivative $\partial f/\partial Re$ is found as 9×10^{-7}. With $Re = \rho VD/\mu$, the error in the Reynolds number is

$$\frac{\Delta Re}{Re} = \left[\left(\frac{\Delta\rho}{\rho}\right)^2 + \left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta D}{D}\right)^2 + \left(\frac{\Delta\mu}{\mu}\right)^2\right]^{1/2}$$

The error in each of these terms is assumed as follows:

$$\frac{\Delta\rho}{\rho} = 0.01$$

$$\frac{\Delta V}{V} = 0.05$$

$$\frac{\Delta D}{D} = 0.005$$

$$\frac{\Delta\mu}{\mu} = 0.10$$

and the error in Reynolds number becomes

$$\frac{\Delta Re}{Re} = 0.112$$

where the major portion of the error is involved in the viscosity. Substitution of the specified values for the terms in equation (A1) leads to a total error in the flow coefficient $\Delta K_g/K_g$ of 2.1×10^{-3}.

Expansion Factor

The expansion factor $\Delta Y_g/Y_g$ for a fluid passing through an orifice is a function of the pressure ratio and adiabatic expansion coefficient:

$$Y = f(r', \gamma)$$

where

r' pressure ratio, P_0/P_1

γ adiabatic expansion coefficient

P_1 upstream pressure

The root-sum-square error in the expansion factor is

$$\frac{\Delta Y_g}{Y_g} = \left[\left(\frac{r'}{Y_g}\frac{\partial f}{\partial r'}\right)^2 \left(\frac{\Delta P_o}{P_o}\right)^2 + \left(\frac{\Delta P_1}{P_1}\right)^2 + \left(\frac{1}{Y_g}\frac{\partial f}{\partial k}\Delta k\right)^2\right]^{1/2} \tag{A2}$$

The partial derivatives can be evaluated from figure 72 of reference 22 on a finite difference basis. For values of $k = 1.4$, $r' = 0.9$, $Y = 0.97$, and $\beta = 0.25$, the partial derivatives are

$$\frac{\partial f}{\partial r'} = 0.3$$

$$\frac{\partial f}{\partial k} = 0.03$$

If the pressures are assumed to be measured to 1 percent and $\Delta k = 0.02$, the total error $\Delta Y_g/Y_g$ in the expansion factor computed from equation (A2) is 4×10^{-3}.

Orifice Area

The total error $\Delta A/A$ in knowledge of the orifice area must take into account the area change with temperature. The area of the orifice is given by

$$A = \frac{\pi}{4}\left[d_o(1 + a\Delta T)\right]^2$$

where

d_o diameter measured at T_o

The total error in the area determination is given by

$$\frac{\Delta A}{A} = 2\left\{\left[\left(\frac{\Delta d_o}{d_o}\right)^2 + \left[\frac{a(T - T_o)}{1 + a(T - T_o)}\right]^2\left[\left(\frac{\Delta a}{a}\right)^2 + \left(\frac{\Delta(T - T_o)}{T - T_o}\right)^2\right]\right]\right\}^{1/2}$$

If the values for the terms, $\Delta d_o/d_o = 0.001$, $T - T_o = 1500$, $a = 10^{-5}$, $\Delta a/a = 0.05$, and $\Delta(T - T_o)/T - T_o = 0.00375$ are assumed, the total error $\Delta A/A$ in the area is 2.5×10^{-3}.

Factor B

The uncertainty in measuring total two-phase weight flow with the use of equation (7) was given as ±1.5 percent in reference 18. A portion of this is involved with uncertainty in the empirical correlating factor B. Reference 18 indicates that the standard deviation of B was 0.75 percent. Therefore the random error in the factor B is assumed equal to its probable error (which is two-thirds of the standard deviation) or $\Delta B/B = 0.005$. The uncertainty in the remaining factors in equation (9) are assumed as follows: the weight flow $\Delta w/w$ was 0.01; the differential pressure measurement $\Delta p/p$ was 0.01; and the specific volume measurements $\Delta v_g/v_g$ and $\Delta v_f/v_f$ were 0.01. Thus, values for all terms within the summation signs are established.

APPENDIX B

DERIVATION OF DIFFERENCES

Calorimeters

Under the assumption that no subcooling or superheating occurs in the devices, the enthalpy h_2 in equation (3) becomes either a saturated vapor enthalpy or a saturated liquid enthalpy for calorimetric devices. The differences in the values of quality computed from two sets of property data then follow directly from equation (3) as

Heating calorimeter:

$$\Delta x_{HC} = (1 - x')\left(\frac{h'_{fg} - h_{fg}}{h_{fg}}\right)$$

Condensing calorimeter:

$$\Delta x_{CC} = -x'\left(\frac{h'_{fg} - h_{fg}}{h_{fg}}\right)$$

Throttling calorimeter:

$$\Delta x_{TC} = \frac{h'_{fg}\left(h_{g,1} - h_{g,2}\right) - h_{fg}\left(h'_{g,1} - h'_{g,2}\right)}{h'_{fg}h_{fg}}$$

For this appendix, the primed variables represent data from reference 16, while the unprimed variables are data for potassium from reference 21. To eliminate the enthalpy terms as variables and obtain expressions for these differences as a function of saturation temperature, plots of h'_{fg} against h_{fg} and h'_g against h_g were constructed. The points were plotted for specific values of saturation temperatures, and from the curves the following linear relations were obtained:

$$h_{fg} = 0.773\ h'_{fg} + 212$$

$$h_g = 1.75\ h'_g - 882$$

Also, from a plot of h'_{fg} against temperature, the following relation was obtained:

$$h'_{fg} = -0.152\ T + 1039$$

Eliminating the enthalpies in the difference equation and using equation (3) yielded the following difference equations:

$$\Delta x_{HC} = (1 - x')\left(\frac{24 - 0.0345\ T}{1015 - 0.117\ T}\right) \tag{B1}$$

$$\Delta x_{CC} = -x'\left(\frac{24 - 0.0345\ T}{1015 - 0.117\ T}\right) \tag{B2}$$

$$\Delta x_{TC} = (1 - x')\left(\frac{806 - 0.149\ T}{1015 - 0.117\ T}\right) \tag{B3}$$

Flow Measurement System

Variations in the available values of the specific volumes of the saturated fluids result in differences in computed values of quality in the flow measurement technique. To obtain the difference equation, the following substitutions are made for terms in equation (8):

$$C_3 = \frac{K_y Y_y A}{w}(2Gp)^{1/2}$$

$$C_4 = B\frac{K_g}{K_f}Y_g$$

$$Z = \left(\frac{1}{v_g}\right)^{1/2}$$

$$U = \left(\frac{v_f}{v_g}\right)^{1/2}$$

The terms of interest are Z and U. The equation for the flow measurement technique becomes

$$x = \frac{C_3 Z - C_4 U}{1 - C_4 U} \tag{B4}$$

Let the primed variables Z' and U' refer to specific volumes given by reference 16 and the unprimed variables Z and U refer to the data for potassium from reference 21. The difference equation becomes

$$\Delta x = x' - \frac{x'\left(\frac{Z}{Z'} - C_4 U' \frac{Z}{Z'}\right) + C_4\left(\frac{Z}{Z'} U' - U\right)}{1 - C_4 U}$$

where C_3 has been eliminated by use of equation (B4).

The terms Z/Z', $U' Z/Z'$, and U were plotted as a function of saturation temperature and the following relations were obtained:

$$\frac{Z}{Z'} = 1.177 - 9.11\times10^{-5}\ T$$

$$U' \frac{Z}{Z'} = 9.56\times10^{-5}\ T - 0.108$$

$$U = 9.56\times10^{-5}\ T - 0.109$$

The values for the terms in the constant C_4 were assumed as

$$B = 1.26$$

$$K_f = K_g$$

$$Y_g = 1.0$$

$$C_4 = 1.26$$

The difference equation for the flow-measurement technique becomes

$$\Delta x_{FM} = x'\left(\frac{9.09\times10^{-5}\ T - 0.175}{1.13 - 12.0\times10^{-5}\ T}\right) \tag{B5}$$

where $1.31\ x' >> 1.26\times10^{-3}$.

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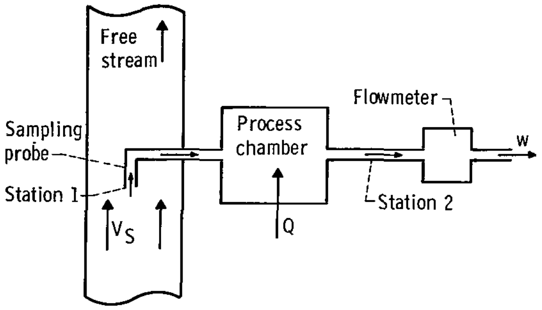

Figure 1. - Calorimeter. Energy added Q is positive for heating calorimeter, negative for condensing calorimeter, and zero for throttling calorimeter.

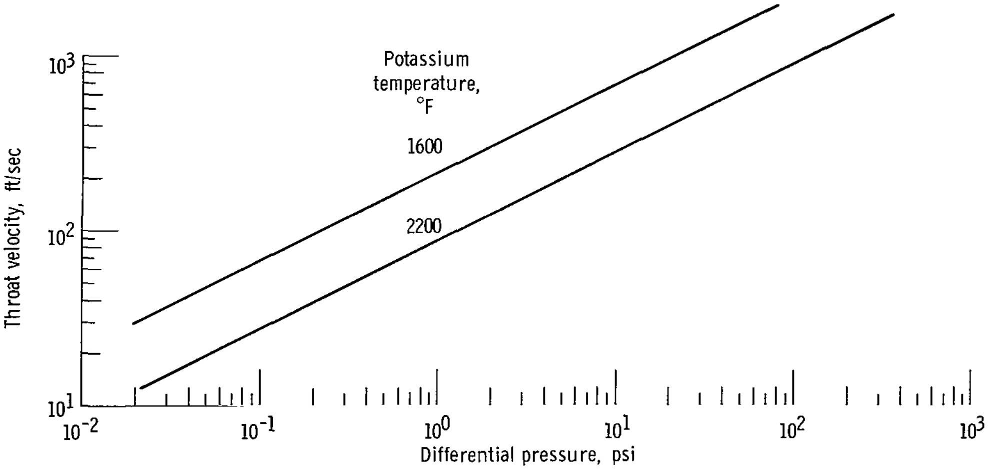

Figure 2. - Variation of differential pressure with velocity.

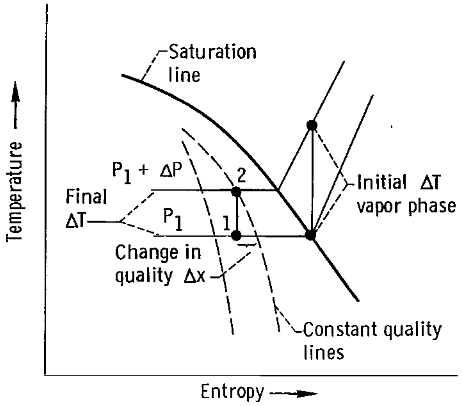

Figure 3. - Temperature-entropy diagram.

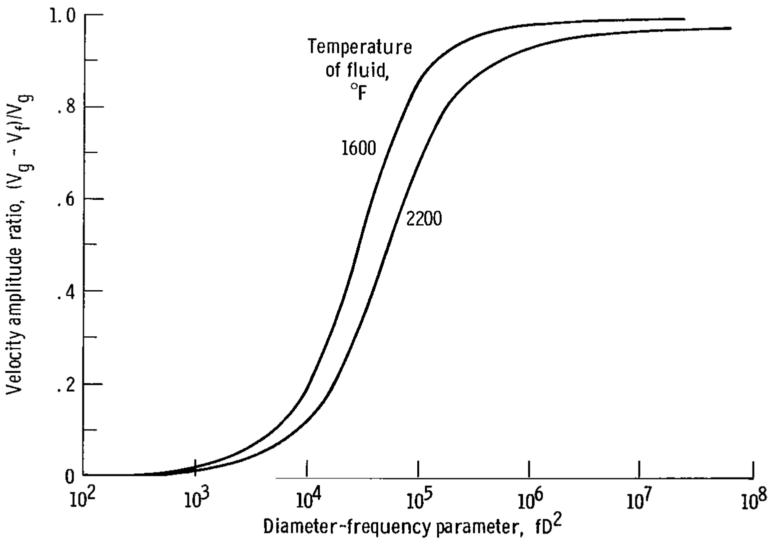

Figure 4. - Variation of velocity amplitude ratio with diameter frequency parameter.

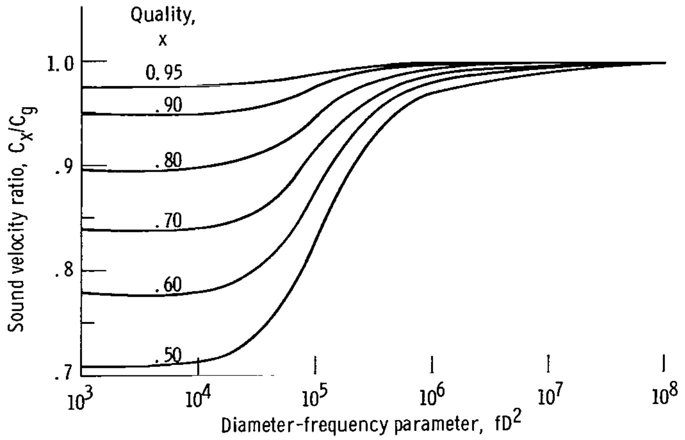

Figure 5. - Variation of sound velocity ratio with diameter-frequency parameter for potassium at 1600° F.

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