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SUMMARY

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The use of a throttling calorimeter for vapor-quality measurements in liquid-metal systems is discussed. The throttling calorimeter is limited to measurements in the quality range 0.91 to 1.00 for potassium based on stream temperatures between 1600° and 2200° F and expansion pressures from 1 to 10 pounds per square inch absolute. Pressure and temperature measurement errors introduce a maximum uncertainty of ±0.005 based on the assumption of the availability of accurate property values, while heat losses are estimated to produce uncertainties of less than ±0.005. The problem of sampling two-phase streams is discussed, and limits are placed on the degree of control required for the sampling system. These results are typical of those that would be expected for other liquid metals.

Author

INTRODUCTION

The need for large amounts of electric power in space vehicles has resulted in proposals of Rankine-cycle systems which use alkali metals as working fluids. A number of analyses have been made of the thermodynamic characteristics and requirements of such cycles with emphasis placed on minimizing system weight and in particular radiator weight (refs. 1 and 2). It has been concluded that Rankine cycles appear feasible with operating temperatures limited by material considerations to the 1200° to 2200° F range. Extensive experimental research and development is required, however, if the systems are ever to couple maximum temperatures for efficient operation with adequate reliability for long operating life in space. To obtain the experimental data, accurate measurements must be made of temperature, pressure, mass flow, and quality at various points in the high-temperature liquid-metal streams.

A review of the available research literature and development-contract listings indicates that measurements of pressure, temperature, and mass flow are receiving some attention. There is a very limited amount of information, however, with respect to the measurement of quality in high-temperature liquid-metal vapor streams. Numerous suggestions have been made for the measurement of quality based on acoustics, nuclear absorption, and other fluid properties. Most of these suggestions require extensive development of complex instrumentation systems and in many cases are limited to only one particular application.

Measurement problems have often been complicated by striving to obtain desired rather than required limits on range and accuracy. These required limits can be determined by considering where the measurements are to be made and whether a quantitative or a qualitative measurement is needed. A survey was made at the Lewis Research Center to determine the immediate requirements for quality measurements. It was found there is a need in turbine studies for a device that will measure turbine inlet quality. In general, a saturated vapor is required at the inlet to the turbine for large space-power systems in the interest of minimizing system weight (refs. 1 and 2). Further, the designer and the test engineer involved in turbine work are concerned with the effects of wet vapor on performance and blade erosion that occurs when the inlet quality deviates from the ideal.

An instrument capable of measuring quality in the 95- to 100-percent range would meet this immediate demand for quality measurements in turbine studies. An instrument capable of detecting the existence of small amounts of liquid in a qualitative manner would also satisfy many requirements in other liquid-metal studies. A device that fundamentally meets these limited requirements is a throttling calorimeter. The throttling calorimeter has been used extensively in steam measurements, but limited use of the device has been made in liquid-metals applications. As there appeared to be no reports estimating the accuracy achievable with a throttling calorimeter in liquid metals, this feasibility study was undertaken to determine whether or not a throttling calorimeter would be of practical use in measuring quality in liquid-metal vapor streams.

PRINCIPLE OF OPERATION

A schematic diagram of a throttling calorimeter is shown in figure 1. The throttling calorimeter utilizes a steady-flow adiabatic expansion process in which no work is done by or on the fluid. During the expansion process, an increase in entropy of the mixture occurs and there is a transfer of energy from the vapor to the liquid component of the mixture. Liquid is thereby evaporated. To obtain a measurement of quality, the expansion must proceed until a superheated vapor is achieved in the mixing chamber thus indicating that all liquid has been vaporized. The steady-flow energy equation relating the enthalpy and kinetic energy at sections 1 and 2 is

$$h_1 + \frac{V_1^2}{2gJ} = h_2 + \frac{V_2^2}{2gJ}$$

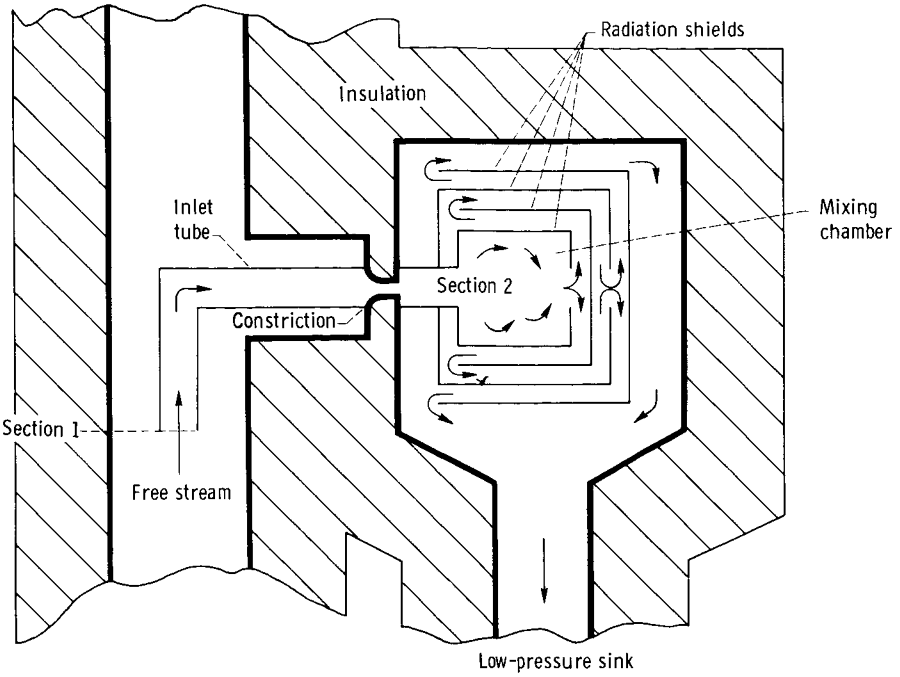

Figure 1. - Schematic diagram of throttling calorimeter.

where

h_1	enthalpy of mixture at section 1
V_1	velocity of fluid at section 1
g	gravitational constant
J	mechanical equivalent of heat
h_2	enthalpy of fluid at section 2
V_2	velocity of fluid at section 2

The enthalpy h_1 is a function of the quality at section 1, the relation being

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

where

$h_{g,1}$	enthalpy of saturated vapor at section 1
x	vapor quality of fluid, ratio of weight flow of vapor to total weight flow at measurement point
$h_{fg,1}$	heat of vaporization of fluid at conditions of temperature or pressure of section 1

Substituting for h_1 in equation (1) and solving for x results in

$$x = 1 - \frac{h_{g,1} - h_2}{h_{fg,1}} - \frac{V_1^2 - V_2^2}{2gJh_{fg,1}}$$

Normally, a calorimeter would be designed to minimize the velocity and therefore the kinetic energy at section 2. Further, as the immediate application of a calorimeter is to measure turbine inlet qualities where the fluid velocity is expected to be less than 100 feet per second, the entire kinetic energy term becomes negligible and is therefore neglected in the remainder of this report. However, if the velocities at the measurement points are several hundred feet per second or greater, the neglection of the kinetic-energy term would introduce appreciable error in the quality measurement. Thus by neglecting the kinetic energy term, the following equation can be used to determine the unknown quality.

$$x = 1 - \frac{h_{g,1} - h_2}{h_{fg,1}} \tag{2}$$

Since the expansion process produces a superheated vapor in the mixing chamber, the enthalpy h_2 is found in thermodynamic property tables using static pressure and temperature measurements made at section 2. Similarly, $h_{fg,1}$ and $h_{g,1}$ are also determined from the tables using static measurements of either the saturated pressure or temperature at section 1.

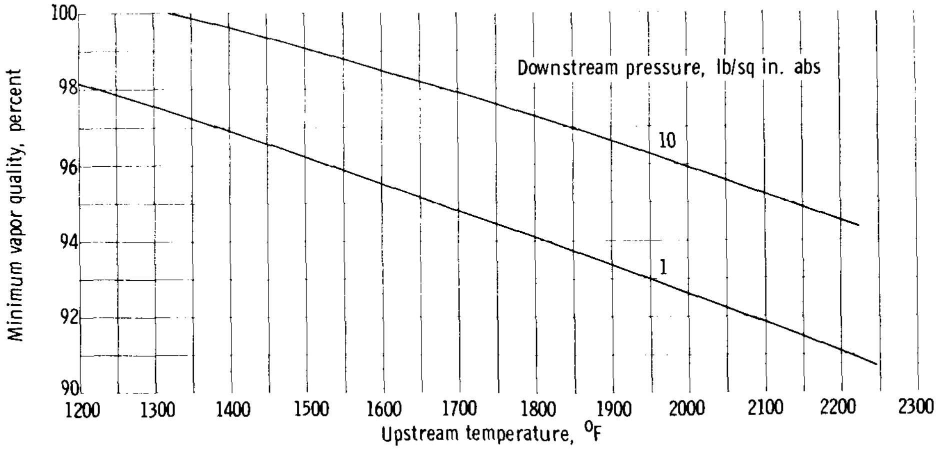

Figure 2. - Minimum quality as function of upstream temperature (data from ref. 3).

RANGE LIMITATION

The range of a throttling calorimeter is limited by the requirement that the fluid be expanded to a superheated condition. As a measurement of enthalpy can be made only on a single-phase fluid, the mixture of unknown quality must be expanded to the extent that superheated vapor is achieved in the mixing chamber. The lowest enthalpy of a vapor which can be measured is that of saturation at the mixing-chamber pressure.

Thus, for a given mixing-chamber pressure, the minimum quality that can theoretically be measured as a function of upstream conditions can be determined. A plot of this minimum quality for potassium is given in figure 2.

This curve was computed by using data from reference 3. If saturation conditions were achieved in the expansion, the quality of the sample would be less than that indicated in figure 2. The range of interest includes temperatures greater than 1600° F, and from practical considerations, mixing-chamber pressures greater than 1 pound per square inch absolute. Thus, use of a throttling calorimeter could be made to measure qualities of potassium as low as 96 percent at 1600° F and 91 percent at 2200° F.

SOURCES OF ERROR AND INSTRUMENT ACCURACY

The error in a measurement of quality using a throttling calorimeter is primarily dependent on three factors: (1) the accuracy by which the enthalpies are determined from pressure and temperature measurements, (2) the amount of heat loss occurring in the calorimeter system, and (3) as in all devices requiring sampling, an error dependent on the degree to which a representative sample of the free stream is obtained. The sections that follow are devoted to a discussion of these sources of error, and their magnitudes are estimated. The discussion is based on a hypothetical instrument with inlet temperatures between 1600° and 2200° F, mixing-chamber temperatures between 1150° and 1450° F, and potassium as the system fluids. The error will be given as a plus or minus value of reading.

Enthalpy Measurements

The error in a quality measurement caused by uncertainties in the enthalpies can be found from the differential form of equation (2):

$$dx = \frac{1}{h_{fg,1}}\left[dh_{g,1} + dh_2 + (1 - x)dh_{fg,1}\right] \qquad (3)$$

where all errors are assumed additive. The terms dx, $dh_{g,1}$, dh_2, and $dh_{fg,1}$ are the uncertainties associated with the determination of the parameters x, $h_{g,1}$, h_2, and $h_{fg,1}$. If it is assumed that the thermodynamic properties of the fluid are accurately known, the probably uncertainty in quality can be evaluated from knowledge of the functional relation between the parameters and the measured variables of temperature and pressure.

Assume the functions f, g, and k exist such that

$$h_{fg,1} = f(P) \quad \text{or} \quad f'(T)$$

$$h_{g,1} = g(P) \quad \text{or} \quad g'(T)$$

$$h_2 = k(P, T)$$

where

P pressure

T temperature

(It should be noted that $h_{fg,1}$ and $h_{g,1}$ are measured at saturation conditions and therefore only a measurement of pressure or temperature is required.) The uncertainty in the parameters becomes equal to

$$dh_{fg,1} = \frac{df}{dP} dP \quad \text{or} \quad \frac{df'}{dT} dT$$

$$dh_{g,1} = \frac{dg}{dP} dP \quad \text{or} \quad \frac{dg'}{dT} dT$$

$$dh_2 = \frac{\partial k}{\partial P} dP + \frac{\partial k}{\partial T} dT$$

The total and partial derivatives are the slopes of the functions f, g, and k at the measurement condition. The functions for potassium are given in figures 3 to 6, which are plots of data from reference 3. The absolute values for the slopes of $h_{fg,1}$ and $h_{g,1}$ at 1600° and 2200° F are given in table I. Also indicated in table I are the values of temperature and pressure at the points where the slopes were measured.

It is estimated that temperatures can be measured to 1/2 percent in the liquid-metal systems, and that pressures can be measured to 1 percent of reading for pressures above 10 pounds per square inch absolute and to ±0.1 pound per square inch for pres-

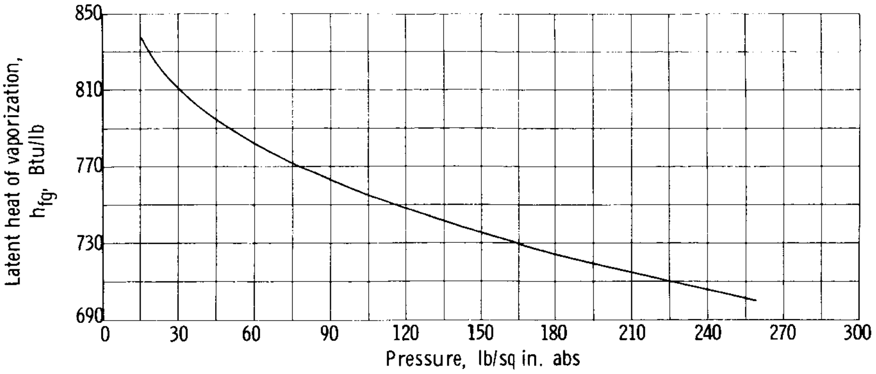

Figure 3. - Latent heat of vaporization as function of saturation pressure for potassium (data from ref. 3).

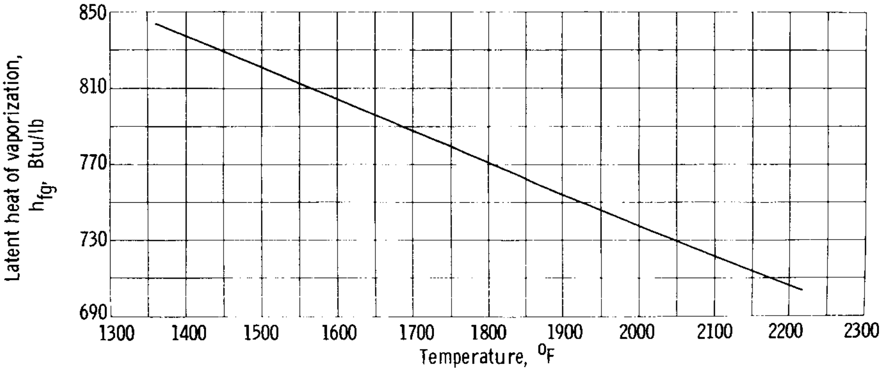

Figure 4. - Latent heat of vaporization as function of temperature for potassium (data from ref. 3).

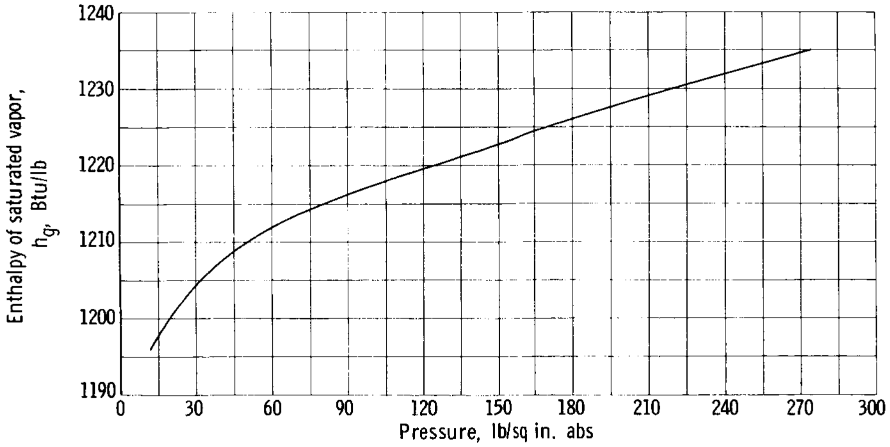

Figure 5. - Enthalpy of saturated vapor as function of pressure for potassium (data from ref. 3).

sures below 10 pounds per square inch absolute. This leads to a maximum uncertainty for $h_{fg,1}$ and $h_{g,1}$ of 2.25 and 1.66 Btu per pound, respectively, in potassium at 2200° F.

Evaluation of the uncertainty in h_2 requires the extrapolation of the property values of reference 3 to the 1150° to 1400° F range. Figure 7 is a plot of the enthalpy of superheated potassium vapor as a function of pressure and temperature. From these curves at 3 pounds per square inch absolute, the $\partial k/\partial T$ is estimated to be 0.17 Btu per pound per °F.

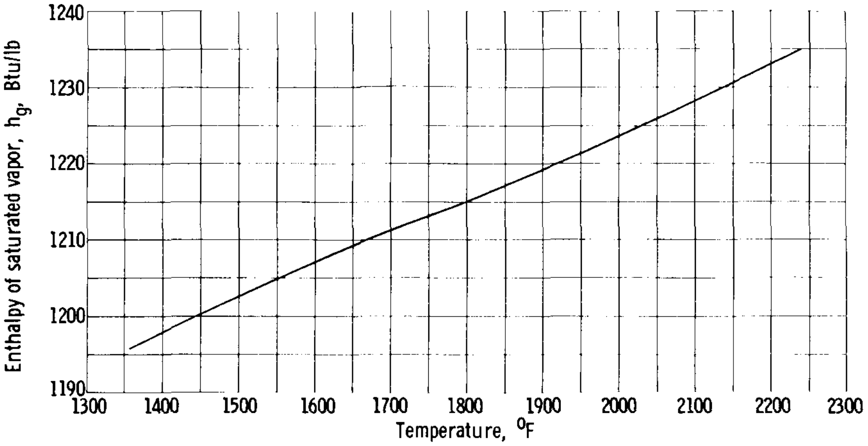

Figure 6. - Enthalpy of saturated vapor as function of temperature for potassium (data from ref. 3).

TABLE I. - SLOPES OF CURVES AND ERRORS IN ENTHALPY MEASUREMENTS FOR POTASSIUM

(a) Latent heat of vaporization

Temperature, T, °F	Pressure, P, lb/sq in. abs	Latent heat of vaporization, h_{fg}, Btu/lb	$\frac{df}{dP}$, Btu/(lb/sq in.)	$\frac{df}{dP}$ dP, Btu/lb	$\frac{df'}{dT}$, Btu/(lb)(°R)	$\frac{df'}{dT}$ dT, Btu/lb
2200	259	701	0.151	1.66	0.307	0.795
1600	38.2	802	.163	1.30	1.045	.402

(b) Enthalpy of saturated vapor

Temperature, T, °F	Pressure, P, lb/sq in. abs	Enthalpy of saturated vapor, h_g, Btu/lb	$\frac{dg}{dP}$, Btu/(lb/sq in.)	$\frac{dg}{dP}$ P, Btu/lb	$\frac{dg'}{dT}$, Btu/(lb)(°R)	$\frac{dg'}{dT}$ dT, Btu/lb
2200	259	1233	0.87	2.25	0.050	0.55
1600	38.2	1207	.28	1.10	.041	.33

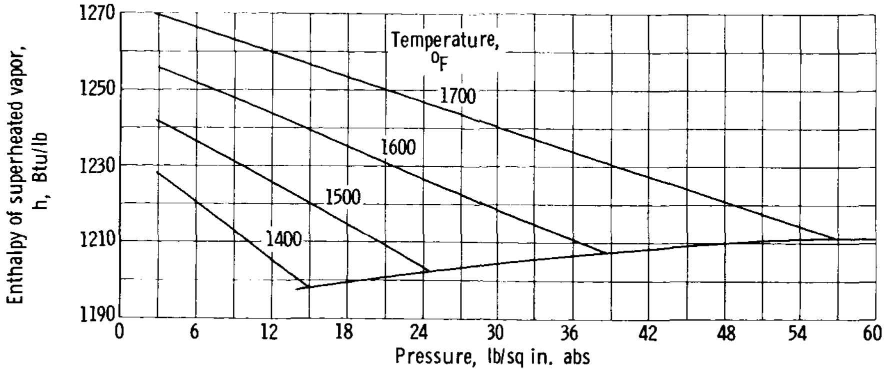

Figure 7. - Enthalpy of superheated potassium vapor as function of pressure and temperature (data from ref. 3).

To obtain $\partial k/\partial P$, the slopes of the constant-temperature lines from figure 7 were plotted on semilog paper as a function of temperature. The curve was extrapolated to 1150° F, at which point the $\partial k/\partial P$ was estimated as 7 Btu per pound per square inch. Thus, the estimated uncertainty in the enthalpy of superheated vapor becomes 1.7 Btu per pound.

Substituting the calculated values of uncertainties in equation (3) and assuming $x = 0.95$ and an upstream temperature of 2200° F result in a maximum error in quality measurement of ±0.005 for potassium. As a comparison, reference 4 states that, with proper instrumentation, a throttling calorimeter for steam is capable of an accuracy of ±0.002. A similar analysis for sodium resulted in errors of the same magnitude.

Thus an analysis of the measurement of enthalpy indicates that a relatively small error is introduced from an instrument accuracy consideration. The assumption, however, that the thermodynamic tables are accurately known is not absolutely true. The error in the tables of reference 3 is estimated at less than 1/2 percent and thus could conceivably introduce an additional uncertainty of ±0.01 in the quality measurement. As better tables become available, this error should be substantially reduced.

Heat Losses

The effect of heat transfer to or from the calorimeter can be seen by including a general-loss term in equation (1). The equation then takes the form

$$h_2 = h_{g,1} - (1 - x)h_{fg,1} - \frac{Q}{\dot{W}} \tag{4}$$

where

Q total heat loss from calorimeter, Btu/hr

$\dot{W}$ weight flow of fluid in calorimeter, lb/hr

Solving the equation for x gives

$$x = 1 - \frac{h_{g,1} - h_2}{h_{fg,1}} + \frac{Q}{\dot{W}h_{fg,1}}$$

Thus, the error in quality when unaccountable heat transfer occurs is equal to

$$\Delta x = \frac{Q}{\dot{W}h_{fg,1}} \tag{5}$$

The effect of heat transfer to or from the calorimeter is to make the measured value of quality higher when heat is transferred into the calorimeter.

From equation (5), it is seen that the error in quality is proportional to the total heat loss and is inversely proportional to the weight flow and the heat of vaporization. The total heat loss is a function of the calorimeter design, which includes the thermal-insulation properties of materials, the convective heat-transfer coefficients of the fluid, and also the system geometry. The heat-transfer coefficients are considered to be minor functions of the flow rates, and thus, for a given fluid, the error in quality may be considered a function of both weight flow and total heat loss.

Figure 1 schematically shows what is considered an ideal throttling calorimeter design from a heat-transfer standpoint. Major emphasis in design should be placed in two areas. First, heat losses in the sampling line connecting the probe to the mixing chamber should be eliminated. One of the simplest means of reducing heat losses in the inlet line is to allow the free stream to circulate around the tube as shown in figure 1 (p. 3). Second, heat losses in the mixing chamber should be eliminated. In throttling calorimeters for steam measurements, use is made of radiation shields as shown in figure 1. The shields not only reduce the radiation loss from the inner mixing chamber but also direct the vapor flow around the shield in such a manner as to reduce thermal-conduction losses.

An analysis has been made of the heat transferred from a fluid in a mixing chamber similar to that shown in figure 1. The analysis was based on a mixing chamber with one radiation shield. Considered were convective heat transfer from the fluid to the various surfaces in the system, radiative interchange between the shield and inside walls, and conductive heat transfer across the outside insulation covering the system. From the analysis, the conclusion was reached that an error in quality of less than 0.01 could be achieved with only one shield and that this could be substantially reduced when using a mixing chamber with two or more radiation shields. The heat-loss error is estimated therefore at less than ±0.005.

Sampling

Obtaining a representative sample of a two-phase mixture is difficult in that it requires a probe which captures liquid droplets and vapor in proportion to that present in the free stream. Reference 4 outlines practices which should be followed in order to obtain a representative sample from steam systems. These recommendations are also applicable to liquid-metal systems and may be summarized by the following design criteria: (1) the probe tip must be as thin as possible so as not to appreciably disturb the flow pattern in the free stream, (2) the probe must be positioned in the system at a point where the free stream is in a homogeneous condition and at uniform velocity, and (3) the velocity of the fluid at the probe entrance should be identical to that of the free stream. The first two requirements can be readily met in design, while the condition for the third is difficult to achieve and will be discussed in some detail in the paragraphs that follow.

When differences exist between the probe-entrance and free-stream velocities, the streamline flow in the vicinity of the probe will be altered from straight to curved lines. As the liquid drops are of greater density than the vapor, they will tend to remain on straight paths and not follow the curved vapor streamlines. Consequently, either more or less liquid in proportion to vapor will be captured by the probe, and a difference between the probe and free-stream qualities will result. Numerous methods have been used to analyze thoroughly flow patterns and droplet trajectories around objects (refs. 5 and 6). These methods are based on parameters such as droplet sizes and distributions, initial flow patterns, drag coefficients, and a number of other variables that are not well defined for liquid-metal systems. Therefore, the following simplified analysis was made to estimate the maximum allowable difference between the free-stream and probe velocities.

The assumption is made that the droplets are not deflected by the free stream. The number of droplets entering the probe is proportional to the free-stream velocity and the inlet cross-section area of the probe. The quality in the probe is given as

$$x_P = \frac{\dot{W}_g}{\dot{W}_g + \dot{W}_\ell} \tag{6}$$

where

$\dot{W}_g$	weight flow vapor entering probe, lb/sec
$\dot{W}_\ell$	weight flow liquid entering probe, lb/sec

The droplets are assumed to occupy a negligible volume in the stream but, for a given stream volume, have an average specific volume $\overline{v}_f$ (cu ft/lb liquid). The average specific volume of the liquid is defined as

$$\overline{v}_f = \frac{\mathcal{V}}{n\rho \frac{D^3\pi}{6}}$$

where n is the number of droplets in a volume $\mathcal{V}$ (cu ft) of the free stream, ρ is the liquid density (lb/cu ft), and D is the droplet diameter (ft). Thus

$$\dot{W}_\ell = \frac{V_s A_P}{\overline{v}_f}$$

$$\dot{W}_g = \frac{V_P A_P}{v_g}$$

where

V_s	stream velocity, ft/sec
A_P	probe area, sq ft
V_P	probe velocity, ft/sec
v_g	specific volume of the vapor, cu ft/lb

Substituting for $\dot{W}_\ell$ and $\dot{W}_g$ yields

$$x_P = \frac{1}{1 + \frac{V_s}{V_P}\frac{v_g}{\overline{v}_f}} \tag{7}$$

or with $V_s/V_P = \overline{V}$

$$x_p = \frac{1}{1 + \overline{V}\,\frac{v_g}{v_f}}$$

From equation (6) the free-stream quality is given when $\overline{V} = 1$. The difference between free-stream and probe qualities or sampling error becomes

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

where x is free-stream quality and

$$\frac{v_g}{v_f} = \frac{1 - x}{x}$$

Thus the sampling error is a function of the free-stream quality and the velocity ratio. A plot of equation (7) is given in figure 8.

It can be seen that large differences are introduced between the probe and free-stream qualities when velocity ratios are not equal. It is felt that a good criterion for a probe evaluation would require that the sampling error be less than one-fourth of the

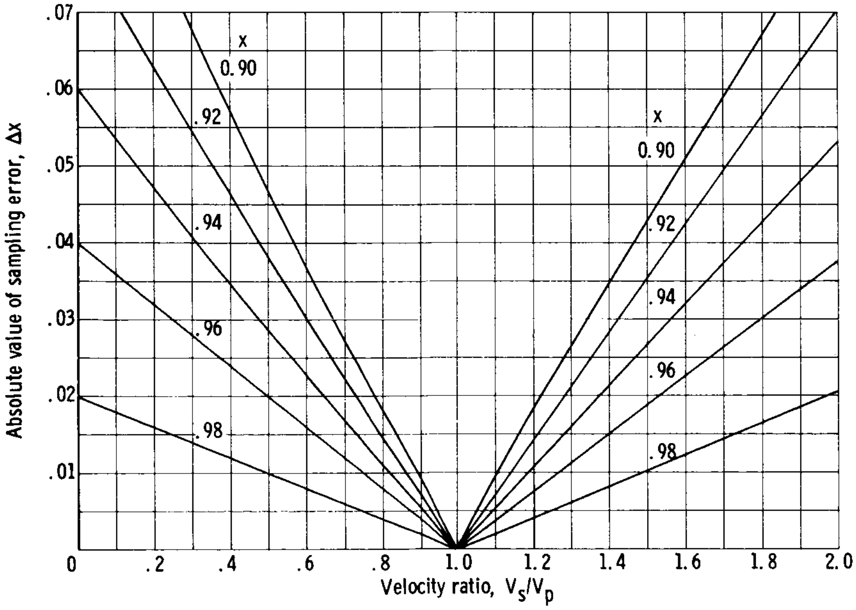

Figure 8. - Absolute value of sampling error as function of velocity ratio and quality.

moisture content of the free stream. This results in the requirement that the velocity ratio be between $0.75 < \overline{V} < 1.25$.

To obtain a representative sample of a two-phase mixture, the velocity in the probe entrance must be controlled to within 0.75 to 1.25 of the free-stream velocity. In practical applications, free-stream flow conditions are varied over wide ranges, and therefore a probe with a variable flow control is required. In a throttling calorimeter, the constriction could take the form of a valve for this purpose. Also required would be a flow measurement in the free-stream and the calorimeter line.

It may be concluded that the accuracy of a throttling calorimeter generally exceeds the accuracy of sampling as is true for a steam calorimeter (ref. 4).

CONCLUDING REMARKS

A throttling calorimeter can be used to measure quality or to give an indication of the presence of liquid droplets in potassium vapor streams. The minimum quality that can be measured is limited by the requirement that superheated vapor be achieved on the downstream side of the mixing chamber. The limit of error resulting from inaccuracies in pressure and temperature measurements is estimated at ±0.005. With proper design, the limit of error due to heat loss should be less than ±0.005. One other error which is difficult to evaluate is that caused by inaccuracies in the tabulated values of enthalpy. When a throttling calorimeter or any device requiring sampling of a two-phase mixture is used, extreme care must be exercised to ensure that a representative sample is obtained from the free stream.

Depending on whether the probe entrance velocity is well controlled and on whether superheated vapor is achieved in the expansion process, it is concluded that the calorimeter can be used for making either quantitative or qualitative measurements of fluid conditions. A comparable instrument accuracy should be expected for throttling calorimeters using metals other than potassium.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 23, 1965.

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