Pesco Products Division  
Borg-Warner Corporation  
24700 North Miles Road  
Bedford, Ohio  

Attention: Mr. L. J. Schafer  

Subject: Monthly Progress Report No. 1  
Subcontract to Prime Contract No. AF 33(616)-5810  
Analytical Investigation of Two-Phase Vapor-Liquid Ratio Measuring Systems  

Gentlemen:  

1. A literature survey has been initiated to determine all available information on two-phase gas-liquid fluid flow and the metering of such flows. This survey will cover the period 1955 (when our report, WADC Technical Report 55-422 Part 1 "Review of the Literature on Two-Phase (Gas-Liquid) Fluid Flow in Pipes", was issued) to the present. Specifically the following was done during the month.  
   a. A comprehensive survey was made of the indexing and abstracting journals in the Georgia Tech Library. Seventy-four references were found.  
   b. Letters requesting lists of theses on the above subject were sent to 36 libraries of universities and engineering colleges that furnished us this type of information during our previous literature survey.  
   c. An ASTIA Field-of-Interest Register was completed and forwarded to you for approval. When approval has been granted, the pertinent ASTIA documents will be surveyed.  

2. Some physical properties data on hydrogen have been compiled. However, this compilation is by no means complete but, before proceeding further in this connection, we will contact you to see what data you can make available to us.  

3. Currently known methods and instruments for measuring vapor-liquid ratios in two-phase systems are being evaluated and new or improved techniques are being considered.
4. Methods and techniques for predicting flow patterns, pressure drops and liquid and vapor velocities are being investigated for the two-phase flow of hydrogen.

Respectfully submitted,

Henderson C. Ward
Project Director

Approved:

T. W. Jackson, Head
Mechanical Sciences Division
LIBRARY DOES NOT HAVE MONTHLY PROGRESS REPORT # 2
December 31, 1958

Pesco Products Division
Borg-Warner Corporation
24700 North Miles Road
Bedford, Ohio

Attention: Mr. L. J. Schafer

Subject: Monthly Progress Report No. 3
Subcontract to Prime Contract No. AF 33(616)-5810
Analytical Investigation of Two-Phase Vapor-Liquid Ratio Measuring Systems

Gentlemen:

1. Procurement and study was continued of the more promising references obtained during the literature survey and from replies received to our requests to other libraries for lists of theses on two-phase gas-liquid fluid flow.

2. Evaluation of currently known methods and instruments for measuring vapor-liquid ratios in two-phase flow systems and consideration of new or improved techniques was continued.

3. Investigation was continued of methods and techniques for predicting flow patterns, pressure drops and liquid and vapor velocities for the two-phase flow of hydrogen.

4. As of December 31, an estimated total of $2,450.85 has been spent. The breakdown is as follows:

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Respectfully submitted:

Henderson C. Ward
Project Director

Approved:

T. W. Jackson, Chief
Mechanical Sciences Division
Pesco Products Division  
Borg-Warner Corporation  
24700 North Miles Road  
Bedford, Ohio

Attention: Mr. L. J. Schafer

Subject: Monthly Progress Report No. 4  
Subcontract to Prime Contract No. AF 33(616)-5810  
Analytical Investigation of Two-Phase Vapor-Liquid Ratio Measuring Systems

Gentlemen:

1. Procurement and study of the more promising references obtained during the literature survey was continued.

2. Evaluation of currently known methods and instruments for measuring vapor-liquid ratios in two-phase flow systems and consideration of new or improved techniques was continued.

3. Investigation of methods and techniques for predicting flow patterns, pressure drops and liquid and vapor velocities for the two-phase flow of hydrogen was continued. A general method, based on fundamental principles, for predicting these quantities during two-phase evaporating flow has been selected for further study. This method has been applied only to water over a limited pressure and tube size range. Therefore, application to hydrogen would require experimental verification.

4. Compilation of pertinent physical properties data on hydrogen was continued.

Respectfully submitted,

Henderson C. Ward  
Project Director

Approved:

T. W. Jackson, Chief  
Mechanical Sciences Division
March 2, 1959

Pesco Products Division
Borg-Warner Corporation
24700 North Miles Road
Bedford, Ohio

Attention: Mr. L. J. Schafer

Subject: Monthly Progress Report No. 5
Subcontract to Prime Contract No. AF 33(616)-5810
Analytical Investigation of Two-Phase Vapor-Liquid Ratio Measuring Systems

Gentlemen:

1. Evaluation of currently known methods and instruments for measuring vapor-liquid ratios in two-phase flow systems and consideration of new or improved techniques were continued.

2. In order to evaluate and become familiar with the general method, referred to in last month's report, for predicting pressure drops, flow patterns, and liquid and vapor velocities during two-phase evaporating flow, calculations have been started on water. When these are completed, calculations will be made for oxygen or nitrogen and then hydrogen. These calculations will be approximate since an empirical factor, which must be determined experimentally, appears in the equations. The calculations will indicate, however, the sensitivity of the equations to the physical properties of the fluids and, consequently, their suitability for hydrogen. If the method does appear suitable and since it yields the liquid and vapor velocities and flowing V/L ratio by calculation, the only experimental V/L measurement needed will be the static or holdup V/L ratio for which instruments are available. The present instruments, of course, will probably require modification for the hydrogen system.

3. Compilation of pertinent physical properties data on hydrogen was continued and was begun for oxygen and nitrogen.

Respectfully submitted,

Henderson C. Ward
Project Director

Approved:

T. W. Jackson, Chief
Mechanical Sciences Division
Pesco Products Division
Borg-Warner Corporation
24700 North Miles Road
Bedford, Ohio

Attention: Mr. L. J. Schafer, Jr.

Subject: Monthly Progress Report No. 6
Subcontract to Prime Contract No. AF 33(616)-5810
Analytical Investigation of Two-Phase Vapor-Liquid Ratio Measuring Systems

Gentlemen:

1. On March 18 and 19, your Dr. Prelowski and Mr. Crabs visited Georgia Tech and discussed with our personnel various technical aspects of our contract and of the overall contract. Our progress and plans for completing our work were reviewed and the assumptions involved in calculating pressure drops and V/L ratios during the two-phase flow of hydrogen were discussed. These discussions were most beneficial to us, and we hope to your personnel also.

2. The calculations, referred to in last month's report, for the two-phase evaporating flow of water were continued.

3. Evaluation of currently known methods and instruments for measuring vapor-liquid ratios in two-phase flow systems and consideration of new or improved techniques were continued.

4. Compilation of pertinent physical properties data of hydrogen, nitrogen and oxygen was continued.

5. Work was begun on bringing our literature survey on two-phase flow up to date and putting the references already obtained in such form that this survey can be incorporated in our final report.

6. As of March 31, an estimated total of $5,066.85 has been spent. The breakdown is as follows:

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Respectfully submitted,

Henderson C. Ward
Project Director

Approved:

T. W. Jackson, Chief
Mechanical Sciences Division
May 1, 1959

Pesco Products Division
Borg-Warner Corporation
24700 North Miles Road
Bedford, Ohio

Attention: Mr. L. J. Schafer, Jr.

Subject: Monthly Progress Report No. 7
Subcontract to Prime Contract No. AF 33(616)-5810
Analytical Investigation of Two-Phase Vapor-Liquid Ratio Measuring Systems

Gentlemen:

1. Work was continued on bringing our literature survey on two-phase flow up to date and putting the references already obtained in such form that this survey can be incorporated in our final report.

2. Work was begun on the other parts of our final report. Three draft copies of this report will be submitted to you by June 1.

Respectfully submitted,

Henderson C. Ward
Project Director

Approved:

T. W. Jackson, Chief
Mechanical Sciences Division
May 29, 1959

Pasco Products Division
Borg-Warner Corporation
24700 North Miles Road
Bedford, Ohio

Attention: Mr. L. J. Schafer, Jr.

Subject: Monthly Progress Report No. 8
Subcontract to Prime Contract No. AF 33(616)-5510
Analytical Investigation of Two-Phase Vapor-Liquid Ratio Measuring Systems

Gentlemen:

1. During the month the draft copy of the final report was completed and three copies are forwarded herewith.

Respectfully submitted,

Henderson G. Ward
Project Director

Approved:

T. W. Jackson, Chief
Mechanical Sciences Division
ANALYTICAL INVESTIGATION OF TWO-PHASE VAPOR-LIQUID
RATIO MEASURING SYSTEMS AND
TWO-PHASE FLOW LITERATURE SURVEY SUPPLEMENT

By

Henderson C. Ward, J. Elmer Rhodes,
Waldemar T. Ziegler and Laurence W. Ross

Engineering Experiment Station
of the Georgia Institute of Technology
Atlanta, Georgia

August 1959

Wright Air Development Center
ANALYTICAL INVESTIGATION OF TWO-PHASE VAPOR-LIQUID RATIO MEASURING SYSTEMS AND TWO-PHASE FLOW LITERATURE SURVEY SUPPLEMENT

By

Henderson C. Ward, J. Elmer Rhodes, Waldemar T. Ziegler and Laurence W. Ross

Engineering Experiment Station
of the Georgia Institute of Technology
Atlanta, Georgia

August 1959

Wright Air Development Center
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FOREWORD

This report was prepared by Henderson C. Ward, J. Elmer Rhodes, Waldemar T. Ziegler and Laurence W. Ross of the Engineering Experiment Station of the Georgia Institute of Technology, Atlanta, Georgia on a subcontract with Pesco Products Division, Borg-Warner Corporation under Prime Contract No. AF 33(616)-5810. The work was administered by Mr. L. J. Schafer, Jr. of Pesco Products Division, Borg-Warner Corporation.
ABSTRACT

In two-phase flow the $V/L$ ratio, the ratio of vapor volume flow rate to liquid volume flow rate, is not amenable to direct measurement when the two phases cannot be separated and then the flow rates separately observed. The $V/L$ ratio can be calculated from measurements of pressure and temperature, static hold-up ratio, total mass flow rate and total momentum flow rate. Only the principle of continuity and some physical definitions are invoked to derive this result.

Physical principles involved in measuring static hold-up and rate of momentum flow are well understood ones, but the development of suitable instruments based on these principles has not yet been made.

A program is outlined for completely characterizing the flow from measurements of temperature and pressure and estimates of heat leak into the pipe. From this characterization the $V/L$ ratio or any other parameter of the flow can be ascertained. This program requires some experimental development, however.

A summary of physical properties of hydrogen currently available has been assembled to facilitate calculations like the foregoing involving two-phase flow of hydrogen.

A literature survey on two-phase flow has been made which supplements a previous survey made in 1955 (1).
### NOMENCLATURE

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<thead>
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<th>Description</th>
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<td>A</td>
<td>cross-sectional area of pipe</td>
<td>ft²</td>
</tr>
<tr>
<td>A_g</td>
<td>cross-sectional area of vapor flow</td>
<td>ft²</td>
</tr>
<tr>
<td>A_l</td>
<td>cross-sectional area of liquid flow</td>
<td>ft²</td>
</tr>
<tr>
<td>a</td>
<td>static vapor-liquid ratio defined by equa. (19)</td>
<td>dimensionless</td>
</tr>
<tr>
<td>D</td>
<td>inside diameter of pipe</td>
<td>ft</td>
</tr>
<tr>
<td>d</td>
<td>denotes differential</td>
<td>dimensionless</td>
</tr>
<tr>
<td>e/D</td>
<td>relative roughness</td>
<td>dimensionless</td>
</tr>
<tr>
<td>F_p</td>
<td>interface shear force</td>
<td>lb_f</td>
</tr>
<tr>
<td>F_w</td>
<td>wall shear force</td>
<td>lb_f</td>
</tr>
<tr>
<td>g_c</td>
<td>dimensional constant, 32.17</td>
<td>(ft)(lb_m)/(sec²)(lb_f)</td>
</tr>
<tr>
<td>H</td>
<td>enthalpy of saturated vapor</td>
<td>Btu/lb_m</td>
</tr>
<tr>
<td>h</td>
<td>enthalpy of saturated liquid</td>
<td>Btu/lb_m</td>
</tr>
<tr>
<td>J</td>
<td>dimensional constant, 778</td>
<td>(ft)(lb_f)/Btu</td>
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<tr>
<td>K</td>
<td>relative velocity factor</td>
<td>dimensionless</td>
</tr>
<tr>
<td>z</td>
<td>distance along the pipe</td>
<td>ft</td>
</tr>
<tr>
<td>M</td>
<td>total momentum flow rate</td>
<td>lb_f</td>
</tr>
<tr>
<td>m_g</td>
<td>mass of vapor phase per unit length of pipe</td>
<td>lb_m/ft</td>
</tr>
<tr>
<td>m_l</td>
<td>mass of liquid phase per unit length of pipe</td>
<td>lb_m/ft</td>
</tr>
<tr>
<td>P</td>
<td>pressure</td>
<td>lb_f/ft²</td>
</tr>
<tr>
<td>Q</td>
<td>heat transferred</td>
<td>Btu/lb_m</td>
</tr>
<tr>
<td>T</td>
<td>temperature</td>
<td>°F</td>
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<tr>
<td>V/L</td>
<td>ratio of vapor volumetric flow rate to liquid volumetric flow rate</td>
<td>dimensionless</td>
</tr>
<tr>
<td>V_g</td>
<td>average velocity of vapor phase</td>
<td>ft/sec</td>
</tr>
<tr>
<td>V_l</td>
<td>average velocity of liquid phase</td>
<td>ft/sec</td>
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</table>
$\overline{V}_p$  average interface velocity  
$v_g$  specific volume of vapor  
$v_l$  specific volume of liquid  
$W$  total mass flow rate  
$W_g$  mass flow rate of vapor phase  
$W_l$  mass flow rate of liquid phase  
$x$  flowing quality defined by equa. (4)  
$y$  static quality defined by equa. (6)  
$\mu$  viscosity  

Subscripts

c denotes commencement of evaporation  
g denotes vapor phase  
l denotes liquid phase  
o denotes pipe outlet
I. INTRODUCTION

Increased usage of cryogenic fuels in propulsive systems in recent years and current investigations of their application to such systems in the future have emphasized a need for a better understanding of the fluid mechanics involved in their transfer and means of calculating and measuring the controlling variables. In many of these transfer systems, a combination of single-phase and two-phase flow occurs and current investigations are being conducted in both flow regions.

The present work, as summarized in this report, is concerned only with two-phase flow and in particular with means of measuring the vapor-liquid ratio, $V/L$, during such flow. The fluid of interest here is hydrogen, and, while the results are generally applicable to other fluids, they are influenced to a considerable degree by the physical properties of hydrogen. This study was analytical only and involved no experimental work.

II. LITERATURE SURVEY

A literature survey (1) was made on two-phase flow in 1955 as part of a previous study. This survey has been brought up to date and the additional references found are contained in Appendix B.

The references cited in this study are listed in the Bibliography.

III. TWO-PHASE FLOW ANALYSIS

1. Vapor-Liquid Ratio

One of the important parameters in two-phase flow is the ratio of the volumetric flow rate of vapor to the volumetric flow rate of liquid, designated here as $V/L$. In the system of interest, liquid hydrogen and its vapor, the $V/L$ ratio will vary from section to section in the transfer system and consequently the following discussion is concerned with the $V/L$ ratio at a particular section in the system under steady-state conditions.

The continuity equations for each phase are

$$\frac{\dot{V}}{g} A_g = W_g$$  (1)
$$\frac{\dot{V}}{l} A_l = W_l$$  (2)

Dividing equation (1) by equation (2) gives

$$\frac{\frac{\dot{V}}{g} A_g}{\frac{\dot{V}}{l} A_l} = \frac{W_g}{W_l}$$  (3)

Defining $x$ as the flowing quality

$$x = \frac{W_g}{W_g + W_l} = \frac{W_g}{W}$$  (4)
where

\[ W = W_g + W_L \]  

(5)

and \( y \) as the static quality

\[
y = \frac{m\,\text{dz}}{m\,\text{dz} + m_L\,\text{dz}} = \frac{\frac{\text{dz}}{\text{dz}}}{\frac{\text{dz}}{\text{dz}} + \frac{\text{dz}}{\text{dz}}} = \frac{A\,\text{dz}}{A\,\text{dz} + A_L\,\text{dz}} = \frac{A\,\text{dz}}{A\,\text{dz} + \frac{\text{dz}}{\text{dz}}} \]

(6)

the following relationships result

\[ W_g = xW \]  

(7)

\[ W_L = (1 - x)W \]  

(8)

\[ A_g = \frac{\frac{\text{dz}}{\text{dz}}}{1 + \frac{\frac{\text{dz}}{\text{dz}}}{\frac{\text{dz}}{\text{dz}}} + \frac{\text{dz}}{\text{dz}}} \]

(9)

\[ A_L = \frac{\frac{\text{dz}}{\text{dz}}}{1 + \frac{\frac{\text{dz}}{\text{dz}}}{\frac{\text{dz}}{\text{dz}}} + \frac{\text{dz}}{\text{dz}}} \]

(10)

where

\[ A = A_g + A_L \]  

(11)

Letting

\[ K = \frac{V_g}{V_L} \]  

(12)

and substituting equations (7) through (10) and (12) into equation (3) gives

\[ K = \frac{x}{\frac{\text{dz}}{\text{dz}}} \]

(13)

The \( V/L \) ratio is thus expressed as
\[
\frac{V}{L} = \frac{\bar{V}}{v} \frac{A_g}{A_g} = \frac{\bar{v}}{v} \frac{W}{W} \tag{14}
\]

\[
\frac{V}{L} = K \frac{V}{v} \frac{1-y}{1} \tag{15}
\]

\[
\frac{V}{L} = \frac{V}{v} \frac{x}{1-x} \tag{16}
\]

These relationships indicate that the measurement of the \( V/L \) ratio involves the measurement of several other quantities. These are \( \bar{V}, \bar{v}, A_g \), or \( A_f \) (the other being calculated by equation (11) and knowledge of \( A \)) or two of the three quantities \( W_g, W_v, \) and \( W \), and pressure and temperature from which \( v_g \) and \( v_v \) can be obtained. To measure \( A_g \) or \( A_f \) by available methods also requires measurement of pressure and temperature.

While pressure and temperature measurements can be made by standard techniques and warrant no further discussion, the measurements of the other quantities \( \bar{V}, \bar{v}, A_g \) or \( A_f, W_g, W_v \), or \( W \) present difficulties which can better be appreciated by considering the complexities involved. The various types of two-phase flow are indicated in Figure 1 and a given flow system may involve one or more of these types. In addition, the type or types of flow that will occur and the transition points between the flow types in a given system is difficult, and in many cases impossible, to determine without experimental data. It should be pointed out though that evaporating flows such as concern us here are likely to be of the annular type which demands a high relative velocity between the phases. However, it should be emphasized that the maintenance of a high relative velocity between the phases is in turn dependent on the physical properties of the phases which themselves depend on pressure and temperature.

Even in view of the complexity of the flow, either \( A_g \) or \( A_f \) can be measured by known techniques, which will be discussed later, and \( W \) can be readily determined in those cases where single-phase flow precedes or follows the two-phase flow. In order to measure the other quantities, either \( \bar{V} \), \( \bar{v} \) or \( W_g \) and \( W_v \), or \( W \) (if the determination cannot be made in single-phase flow), it is tempting to consider inserting some type of probe into the system for the measurement or to consider some other technique successful in measuring these quantities during single-phase flow. However, in general, none of these techniques are practical and, in fact, there is no known satisfactory method presently available for the direct measurement of these quantities according to a survey of the literature on the general field of two-phase (gas-liquid) flow or as a result of this study. The measurements are, of course, more difficult to make when the requirement is imposed that the measurements be made without disturbing the flow.
Figure 1. Horizontal and Vertical Two-Phase Flow Pattern Sketches.
The recommendation of this study is now made that these quantities be determined indirectly by measuring the total momentum flow rate past a particular section along with \( A_g \) or \( A_\ell \) and pressure and temperature measurements at the same section. In addition, \( W \) must be measured while the system is in single-phase flow but presently the possibility of removing this restriction will be discussed.

The total momentum flow rate past a section is given by

\[
M = \frac{W \bar{V}}{g_c} + \frac{W_\ell \bar{V}_\ell}{g_c}
\]  

(17)

Using the continuity equations (1) and (2) and equations (7) and (8), \( M \) can be expressed as

\[
M = \frac{v_g x^2 w^2}{g_c A_g} + \frac{v_\ell (1-x)^2 w^2}{g_c A_\ell}
\]  

(18)

Now using equations (9) and (10) and letting

\[
a = \frac{v_g}{v_\ell} \frac{\bar{V}}{1-y} = \frac{A_g}{A_\ell}
\]  

(19)

equation (18) can be solved for \( x \), the flowing quality. The result is

\[
x = \frac{av_\ell^2 + \sqrt{a \left[ \frac{g_c AM}{w^2} (v_g + a v_\ell) - v_g v_\ell (1 + a) \right]}}{v_g + av_\ell}
\]  

(20)

Note that \( a \) is the static or holdup vapor-liquid ratio, \( A_g/A_\ell \), and is equal to the flowing vapor-liquid ratio only when the velocities of the two phases are equal.

As indicated by equation (20), \( x \) can be determined from measurements of \( y \), \( W \), \( M \) and pressure and temperature.

Relations Based on Momentum Balance and Energy Balance

The foregoing relations are based only on definitions and the principle of continuity. Additional relations between the variables will reduce the number of independent measurements that have to be made in order to fully characterize the two-phase flow.
In one of the most significant works to date on two-phase evaporating flow, Linning (2) has applied the equations of continuity, momentum and energy separately to each phase in a specific flow type under the five following assumptions.

1. Steady-state conditions exist.
2. The pressure and temperature are constant across any section normal to the flow.
3. The fluid is near thermodynamic equilibrium at all stages in the expansion.
4. The mean velocity of each phase is the same whether derived on the basis of continuity, momentum or energy.
5. The pipe is of constant cross-sectional area and is horizontal.

While Linning considered three types of flow -- annular, stratified, and froth -- only his analysis and results for annular flow will be discussed as they are probably more applicable to the evaporating flow of hydrogen. The annular flow is sketched in Figure 2.

![Diagram of Annular Flow](image)

**Figure 2. Diagrammatic Sketch of a Section of Fluid During Annular Flow.**

Linning obtained the following independent equations for annular flow.

**Continuity:**

\[
\bar{V}_l = \frac{W}{A} (1 - x) \bar{v}_l \left(1 + \frac{V/L}{K}\right) \tag{21}
\]

\[
A_l = \frac{A}{1 + \frac{V/L}{K}} \tag{22}
\]

(These equations follow from equations (2), (4), (5), (10) and (15).)
Overall energy:

\[ 2g_c J \left[ h_c - h + x(H-h) + Q \right] = \frac{\bar{V}_c^2}{c_A} \left[ 1 + x(K^2 - 1) \right] - \left( \frac{V_c}{c} \right)^2 \tag{23} \]

Overall momentum:

\[-A dP - dF_w - \frac{W}{g_c} \left\{ [1 + x(K-1)] \bar{dV}_c \right\} = 0 \tag{24}\]

Liquid momentum:

\[-A dP - dF_w + dF_p - \frac{W}{g_c} (1-x) \bar{dV}_c = 0 \tag{25}\]

Vapor energy:

\[ Jxw dH + \bar{V}_p \frac{dF_p}{2g_c} + \frac{W}{2g_c} \left[ 2xK^2 \bar{dV}_c + (K^2 - 1) \bar{V}_c^2 dx + 2x\bar{V}_c^2 dK \right] = 0 \tag{26}\]

These six independent equations, equations (21) - (26), involve the following seventeen variables (V/L is expressed in terms of these variables by equation (16) and the dependence of each variable on position along the pipe z is implied)

\[ H, h, h_c, A_p, \bar{V}_c, W, A, x, \bar{V}_c, K, P, F_w, F_p, \bar{V}_p, Q, V_c, z \]

Specification of P_c, W, A, Q as a function of position along the pipe, position along the pipe z, and a knowledge of the thermodynamic properties of the phases reduces these variables to eight: A_p, \bar{V}_c, x, K, P, F_w, F_p, \bar{V}_p. Since there are only six independent equations, two additional relationships are required. The additional relationships used by Linning are, first

\[ dF_w = f \frac{D f}{8g_c \bar{V}_c} \bar{V}_c^2 dz \tag{27} \]

expressing the drag on the liquid by the pipe wall. In this equation, f is the standard friction factor for pipe flow and is a function of the liquid phase Reynolds number (D \bar{V}_c / \nu_p \mu_p) and the relative roughness (\epsilon/D) as given in standard references (3).

The second relation is

\[ \frac{\bar{V}_p}{\bar{V}_c} = \left[ 1 + 0.2 \left( \frac{T_c - T}{T_c - T_o} \right)^2 \right] \tag{28} \]
In this equation, $T$ is the temperature at the commencement of evaporation and $T_c$ is the outlet temperature. This relationship was obtained from experimental measurements on the evaporating flow of water in a horizontal 1/8 inch diameter tube 12 feet long. The test range covered initial saturation temperatures between $230^\circ F$ and $250^\circ F$ and mass flow rates between 250 and 500 lb/m$^2$/sec. Linning points out that equation (28) is not a general law but simply covers the range of his experiments.

In establishing equation (28), Linning measured the total momentum flow rate of the two phases combined as they emerged from the end of the tube. This measurement was made using a momentum balance similar to that used by Giffin and Crang (4) in their work in 1946 on small steam nozzles.

Using the eight equations, equations (21)-(28), Linning obtained excellent agreement with his experimental data.

In considering the application of Linning's fundamental equations, equations (21)-(26), to the evaporating flow of hydrogen, the assumptions involved must be examined. Assumption 4 is reasonable and assumptions 1 and 5 can be made applicable. Assumption 2 will be applicable if the heat leakage from the environment is kept small. Assumption 3, in view of the recent work of Caine, Schafer, Burgeson and Prelowski (5,6), is subject to some question. However, as a first approximation, it would appear a reasonable starting point in attempting to correlate experimental data on such a system. Visual observations of the flow in the experimental system would establish the flow type. If the flow is annular, equations (21)-(26) would apply. If the flow is not annular, equations similar to these would be applicable.

For discussion, the flow will be assumed to be annular and it will be further assumed that $F_c$, $W$, $A$, $Q$ as a function of position along the pipe, position along the pipe $z$ and the thermodynamic properties of hydrogen are known. Then by measuring $P$, $T$ and $A_p$ at various pipe sections, the remaining six variables $\bar{V}_c$, $x$, $K$, $F_w$, $F_p$, and $\bar{V}_p$ can be calculated by equations (21)-(26). Rate of momentum flow measurements will serve as a check on $x$ and $K$ while the simultaneous $P$ and $T$ measurements will serve to check assumption 3. With these data, Linning's use of equation (27) to specify $F_w$ can be checked and $V_p$ can be determined.

If equation (27) is applicable and the $\bar{V}_p$ dependence determined, the eight necessary equations are established. These equations can be programmed on a digital computer and the experimental data rapidly analyzed. It should be emphasized that should equation (27) not be applicable, the $F_w$ dependence can be established by experimental data but this involves a major experimental program. Also should it be found that the system is not in thermodynamic equilibrium, it might be possible to modify the equations to account for this.

If the above calculation procedure is applicable, then by measuring $A_p$, $M$, $T$ and $P$ at a particular section in the two-phase flow region, $W$ can be determined from equation (18).

The success of these methods, therefore, must rest on experimental tests.
2. Summary of Two-Phase Flow Analysis

To completely characterize the two-phase flow of hydrogen subject to the validity of Linning's assumptions, the easily measurable quantities, \( P, T, A \) and pipe length must be measured. The heat leak to the pipe, \( Q \), must be estimated and the thermodynamic properties of hydrogen must be in hand. In addition at least two of the less easily obtained variables, \( \bar{V}_L \), \( x \), \( K \), \( F_w \), \( F_p \), \( \bar{V}_p \), \( W \), \( A_p \) must be measured.

To test the assumptions at least 3 of the latter must be measured.

The problems associated with measuring some of these quantities are discussed in the following section.

IV. METHODS OF MEASUREMENT

Our whole discussion of the instrumentation of a system in which hydrogen is flowing in two phases, liquid and vapor, is based upon certain quantities associated with the flow being measurable and certain other quantities being either immeasurable or such that their measurement is impractical. We have recognized that the mass flow rates of each phase are desirable quantities to measure so that the \( V/L \) ratio can be determined. However, we have discovered no way to directly measure them.

We have instead suggested an indirect method of measuring the \( V/L \) ratio during the two-phase flow of hydrogen and this method requires that in addition to temperature and pressure measurements at one or more sections along the flow, that the volume fraction of a section of pipe carrying the flow that contains vapor and the volume fraction that contains liquid at an instant can be measured and further that the total rate of momentum flow past this section can be measured. We will discuss in some detail the principles by which these physical quantities can be measured.

The problem of measuring enough physical quantities associated with the two-phase flow of hydrogen to suitably characterize the flow would be greatly simplified if it were possible to measure the average velocity of each of the two phases separately. We feel that present techniques are inadequate to do this. Indeed even when the two phases are moving with the same velocity as is the case with frothing flow, in which bubbles are entrained uniformly throughout the liquid, measurement of the velocity is impractical.

It is necessary to mention velocity measurement and to discuss in some detail the reasons why it is impractical to measure it directly because there are devices for measuring the velocity of single-phase fluid flow that very naturally come to mind and very naturally have been suggested for measuring velocities in two-phase flow.

Most prominent among these are acoustic methods and we will discuss in some detail the reasons why these are impractical for measuring the velocity or velocities of the two phases of hydrogen when they are coexisting.
The measurement of temperature and pressure is no different for two-phase flow from what it is for single-phase flow. The techniques are well known and the difficulties to be met or avoided are likewise well known. The measurement of temperature and pressure will not be discussed in detail.

1. The Measurement of the Liquid Fraction and the Vapor Fraction in a Pipe

Perhaps the most direct way to measure the fraction of liquid and the fraction of vapor in a horizontal pipe would be to weight a section of the pipe containing the two phases. If temperature and pressure were known the density of each of the two phases would be known or would be available and hence the weight of the contents of a measured section of a pipe would be sufficient to obtain the liquid and vapor fractions. There are however many objections to this direct method. At ambient temperature it might indeed be practical to flexibly connect the two ends of a section of horizontal pipe to the rest of the system and measure the force required to maintain this section of pipe axially coincident with the sections of pipe joining at each end. To accomplish this at the temperature of liquid hydrogen and to do so in a manner that would allow accurate measurement of the weight of a fluid no more dense than hydrogen would at least require invention and great skill in design and execution. If it were necessary to have the fluid system mounted in an accelerating vehicle or device the problems involved in this measurement are even greater. An accurate measurement of acceleration as well as the component of the gravitational field perpendicular to the pipe would have to be measured and accounted for in the computations that yield in the end the liquid and the vapor fractions. This method of measurement has the attraction of being straightforward but except in special cases where it can be applied to advantage, it is certainly not recommended.

A non-mechanical means for measuring the liquid and vapor fractions in a pipe that has received considerable attention is that in which some radiation is projected through the pipe and the fraction of the radiation absorbed is measured from the response of a radiation detector located on the side of the pipe opposite the source. Again pressure and temperature must be known in order that the absorptivity of the two phases can be determined.

It should be recognized at the outset that the flows we are dealing with may be to some extent unstable and the configuration of the distribution of liquid and vapor may vary rapidly from one moment to the next. Consequently the value of a thin pencil of radiation that is made to measure different cross sections of the pipe sequentially is of questionable value. A broader beam of radiation that will traverse the whole section of the pipe being measured at one time seems more apt. For a cylindrical pipe the radiation traversing the center of the pipe must, of course, be given greater weight than that at the edge. In addition, the energy input of this radiation must be considered.

The response time of the Bendix Nuclear Density Gauge, series 804 modified (7), seems to be too great to be satisfactory. A source of radiation should be used that is strong enough so that the signal received by the radiation detector will be well above the noise level, and consequently the response time of the instrument can be made as short as desired. Any radiation hazard arising from the use of the strong source of radiation should be taken care of with proper shielding.
This should be the way to take care of a radiation hazard rather than by using a weak source of radiation, a source too weak to give a practical instrument.

The work of Bobbie L. Richardson reported by the U. S. Atomic Energy Commission (8) indicates that this procedure can be successful. Attention should be given in the selection of radiation to a radiation that is absorbed strongly in hydrogen. Consideration along this line has been given in the preparation of Proposal Number 174 of Olympic Radio and Television (9) in which they propose to use a beam of neutrons for the radiation because of the high neutron scattering cross section of protons. Their suggestion of measuring both the direct beam out of which some of the neutrons have been scattered and also the scattered beam might be developed to some advantage. Their assertion that the proton density in hydrogen vapor is practically negligible compared to the liquid is certainly not true near the critical point and indeed even for equilibrium between liquid and vapor at 20° K the difference in density is not nearly so great as we usually think of as the difference in density between a liquid and a vapor.

Indeed, the fact that the densities of the two phases are not so widely separated would render less sensitive both a radiation absorption scheme and also the direct weighing device scheme mentioned previously. The capacitance device mentioned below would be similarly affected although it is impractical for other reasons.

With specific reference to Olympic Radio's Proposal Number 174, more consideration should be given to the detectors. We have not given this consideration but feel that more appropriate detectors would come out of such consideration.

2. Capacitance Gauges for Measuring Liquid and Vapor Fractions

Allison (10) has suggested and developed to some extent a capacitance bridge in which the capacity of a condenser is measured, this condenser having as its dielectric the fluid under consideration. When each phase is saturated the dielectric constant of the vapor phase is in general less than that of the liquid phase of a fluid. This difference is not so great near the critical point of the fluid as it is where the densities of the two phases are more different. Allison personnel have tested their gauge on two-phase flow in which bubbles were uniformly dispersed through the liquid. For this type of flow the capacitance gauge can, no doubt, be made to work. However, the dielectric constant or rather the average dielectric constant of the two phases averaged over the volume is not the quantity of significance in determining the capacity associated with a pair of plates between which the two phases are flowing. The whole geometry of the flow is of importance. A gauge such as the Allison gauge calibrated on a homogeneous mixture of liquid and vapor would be worthless for ascertaining liquid vapor fractions for annular flow for example, or for stratified flow.

That the capacitance associated with a pair of conductors with two dielectric materials in between depends on the detailed geometry of the two phases can easily be demonstrated if one calculates the capacity between a pair of parallel
plates for two arrangements in which each of two different dielectrics occupy half the volume but are distributed in two different ways. First, consider the material with the high dielectric constant extending all the way from one conducting plate to the other and covering half the area of each plate. The other material, the material with the low dielectric constant, would then likewise extend all the way from one plate to the other and it too would cover half the area of each plate. The capacity for this configuration would be essentially that of two capacitors connected in parallel and the effective capacity would be that for a single dielectric with a dielectric constant equal to the volume average of the constants for the two materials.

Next consider the same two conducting plates with the same amount of each dielectric but this time one dielectric covers one plate completely and extends halfway to the other. The other dielectric would fill the rest of the space covering the other plate and extending halfway to the first plate where it would meet the surface of the first dielectric. The capacity of this arrangement would be essentially that of two condensers in series and would be much less than the first geometrical arrangement. The capacity would be approximately twice the capacity of the condenser filled with the lower dielectric constant.

About the capacitance gauge we conclude that some very clever invention of electrode shapes would be required if liquid and vapor fractions were to be accurately measured for all possible or even for all likely flow configurations.

3. Direct Measurements of the Velocities of the Two Phases

The velocity of a flowing fluid can be inferred from the behavior of the propagation of sound through the fluid between a fixed sound transmitter and a fixed sound receiver. Whether the Doppler shift in frequency of the signal between transmitter and receiver is observed or whether the time for a signal to pass from transmitter to receiver is measured, these devices depend upon the velocity of propagation relative to the fluid itself being dependent only upon the physical properties of the fluid.

The W. L. Maxon Corp. (11) has developed an instrument for measuring fluid flow velocities that is based upon the time required for a signal to pass from a transmitter to a receiver. The transmitter and receiver are located so that one is downstream from the other. They simplify their measurement problem with the use of two transmitters and receivers; one pair has the transmitter downstream from the receiver and the other has the receiver downstream from the transmitter. This instrument has been described in one of their releases (11). They suggest therein that the instrument can be adapted to two-phase flow. They have in mind a flow consisting of bubbles transported in a liquid at essentially the velocity of the liquid. It is possible that their instrument might be so adapted. However it is necessary in order to use this instrument for the measurement of fluid velocity for the velocity of sound in the fluid to be known. Near the saturation line or at saturation in both the liquid and the vapor the velocity of sound varies very rapidly with temperature or with pressure (12).
It is likely that a better understanding of the propagation of sound in saturated fluids, both liquids and vapors, especially near the critical point, must precede the adequate adaptation of this instrument to the measurement of fluid velocities. For flow configurations in which the two phases are not flowing at the same velocity, it does not appear that a sonic method of measurement can be successfully applied.

4. The Metering of Momentum Flow Rate

One of the quantities that we have assumed to be a measurable one is the rate of momentum flow past various sections of the pipe carrying the two phases of hydrogen. A rate of momentum flow or a momentum flow meter has been described in the thesis of Linning (2). In this meter a catching device intercepted all of the fluid being ejected from a tube, reduced the velocity of this fluid to zero before dropping it into a catch basin below. The force required to maintain this catching device was measured with a balance. Now such a device would hardly be applicable to the measurement of rate of momentum flow of cryogenic fluids, particularly when it is desired that the flow be disturbed as little as possible by the measurement.

However, the physical principles involved can be applied to a meter suitable for cryogenic fluids. A return bend in the pipe carrying the fluid must be attached to the stationary pipes by bellows which are spring loaded. There are two forces which will bear against the springs and cause the bellows to expand. The gauge pressure or the difference in pressures between the fluid and the surrounding atmosphere exerted across the cross sections of the bellows would be one of these forces. The other force would be that required to reverse the momentum of the fluid as it rounded the return bend. The first force could be obtained by static pressure measurements at the fixed pipes. The total of these two forces could be obtained from the deflection of the spring loaded bellows and the difference between the two would give the force proportional to the total rate of momentum transfer down the pipe. If the meter is used in an accelerating vehicle or in the presence of vibrations, the appropriate components of these accelerations also must be considered.

The curvature in the return bend should be small enough not to disturb the flow appreciably, and the bellows connections also must not disturb the flow. It will require considerable design skill to meet these requirements.

We do not present a finished and workable design for such an instrument. We only assert that the physical principles embodied in such an instrument are sound and simple and that a workable design appears to be feasible.

5. Other Measurements Considered

The propagation of electromagnetic radiation, in particular light, through a fluid is influenced by the fluid velocity. This influence would be very small however for fluid velocities that are likely to ensue so that instrumentation would be extremely difficult. Also all of the problems that would plague an acoustic measurement would also be present in an optical measurement of this type.
Another device proposed for obtaining the liquid vapor fractions in flowing cryogenic fluids (9) consists of an optical arrangement for counting the number of bubbles passing a given section of pipe and an acoustical device for ascertaining the sizes of these bubbles by observing the frequency of their acoustical resonance. There is nothing basically wrong with this conception, however it should be realized that a long development program must precede the realization of a practical though complicated device based upon these principles. Further, the principles are applicable only to a flow pattern consisting of bubbles entrained in liquid. It would be worthless for annular flow or for stratified flow and possibly for some other forms of flow, mist flow for example.

Another indirect method of obtaining the V/L ratio, based on the work of Dengler and Addoms (13), consists of the measurements of the concentrations at two sections of the transfer system of either a nonvolatile solute in the liquid phase or an inert gas, not soluble in the liquid, in the gas phase along with temperature and pressure measurements. To adapt this method to cryogenic fluids will require considerable development.

V. THE PHYSICAL AND THERMODYNAMIC PROPERTIES OF NORMAL AND PARAHYDROGEN

The equations which have been derived and the instruments discussed in the preceding sections for the two-phase flow of hydrogen assume that the physical and thermodynamic properties of hydrogen are known from the triple point to the critical point. Furthermore, since single-phase flow may also be involved, data regarding the properties of liquid hydrogen under pressure may prove useful. In actual practice it is very probable that essentially pure liquid parahydrogen (20.4° K-equilibrium hydrogen containing 99.79% p-H\(_2\), 0.21% o-H\(_2\)) rather than normal hydrogen (25% p-H\(_2\), 75% o-H\(_2\)) will be the fluid actually transferred. This is so because parahydrogen is stable at 20.4° K, whereas orthohydrogen is slowly converted into parahydrogen with simultaneous release of heat, thus causing excessive evaporation loss on storage. The physical properties of these two fluids differ only slightly though complete comparative data are not available. For many engineering calculations it is probable that the data for a number of properties of p-H\(_2\) and n-H\(_2\) may be used interchangeably without appreciable error. Among these properties are saturated vapor and liquid densities, vapor pressure, heat of vaporization, P-V-T relations for the gas and liquid phases. Among the properties for which significant differences may be expected are thermal conductivity and heat capacity of the gases and perhaps the velocity of sound.

The most extensive compilation of the thermal properties of hydrogen is that of Woolley, Scott and Brickwedde (14) of the National Bureau of Standards. This work covers the literature up to about January, 1947. Johnston and coworkers (15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25) have extended the available data considerably since that time. More recently the National Bureau of Standards at Boulder, Colo. has begun a re-examination of all the available data.

Since this report was completed, an excellent summary of the physical and thermodynamic properties of hydrogen by Scott (37) has been published.
The principal available data on the physical and thermodynamic properties of both normal and parahydrogen which may be of use in the study of single-phase and two-phase flow are summarized in Appendix A. While time has not permitted a definitive analysis of all the available data, it is felt that the data given are adequate for the purpose of this report. The properties discussed are:

1. Critical constants
2. Vapor pressure
3. Saturated liquid and vapor density
4. Heat of vaporization
5. P-V-T relations for the liquid
6. P-V-T relations for the gas
7. Heat capacity
8. Other properties, including velocity of sound, dielectric constant, viscosity, thermal conductivity, thermodynamic charts and tables.

VI. CONCLUSIONS

There is no known way to measure the V/L ratio at some point in two-phase flow in a pipe directly. However, this ratio can be obtained indirectly by at least two methods.

The first method requires measurement of the static hold-up ratio, a, at the section in question, the rate of momentum flow past this section, M, pressure and temperature at the section to obtain the specific volumes of the two phases, \( v_l \) and \( v_g \), and a knowledge of the total mass flow rate, \( W \). \( W \) can be measured where the flow is single phase. Equation (20), here repeated,

\[
x = \frac{a v_l}{\sqrt{\frac{a}{1+a} \left[ \frac{g_c AM}{W^2} (v_g + a v_l) - v_g v_l (1 + a) \right]}}
\]

will yield \( x \) from these data and then equation (16)

\[
\frac{V}{L} = \frac{v_g}{v_l} \frac{x}{1-x}
\]

will give the V/L ratio.

Measurement of the static hold-up, a, and the rate of momentum flow, M, require the development of special instruments. The physical principles on which these instruments must depend are well established, but skill and judgment will be required in the development of the instruments.
The second means requires measurements to completely characterize the flow. Once the flow is characterized, of course, the $V/L$ ratio becomes a known quantity. Subject to a knowledge of the frictional drag on and between the two phases, the measurement of pressure and temperature along a pipe of known dimensions will characterize the flow. This characterization requires data on the thermodynamic properties of the fluid and the assumption of near-equilibrium in the flow.

Expressions for frictional drag have been suggested, but they need experimental verification and modification if experiments so direct.

It is felt that computer techniques can be adapted to perform the characterization from $P$ and $T$ measurements once the expressions for friction forces are verified.
VII. BIBLIOGRAPHY


32. W. T. Ziegler, unpublished work.


The Physical and Thermodynamic Properties of Normal and Parahydrogen

In this Appendix normal hydrogen (n-H₂) refers to hydrogen containing 75% orthohydrogen and 25% parahydrogen. The term parahydrogen (p-H₂) refers to hydrogen containing 99.71% parahydrogen and 0.21% orthohydrogen, the equilibrium composition at 20.4° K. Strictly speaking this composition should be referred to as "20.4° K - equilibrium hydrogen" (e-H₂). In a few instances (for example in Table VI) p-H₂ refers to pure p-H₂ rather than e-H₂. Wherever temperature appears without qualification T in ° K is meant. The ice point is taken to be 0° C = 273.16° K.

1. Critical Constants, Triple Point and Normal Boiling Point (P = 1 atm.)

The critical constants for n-H₂ and p-H₂ are given in Table I.

<table>
<thead>
<tr>
<th></th>
<th>n-H₂</th>
<th>P_c (atm.)</th>
<th>V_c (cc/mole)</th>
<th>Z_c</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_c (° K)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>33.19</td>
<td>12.98</td>
<td>66.95</td>
<td>0.3191</td>
<td>(14)</td>
</tr>
<tr>
<td></td>
<td>33.24</td>
<td>12.797</td>
<td></td>
<td>0.309</td>
<td>(15)</td>
</tr>
<tr>
<td>p-H₂</td>
<td>32.994</td>
<td>12.770</td>
<td>65.5</td>
<td>0.309</td>
<td>(26)</td>
</tr>
</tbody>
</table>

The triple point temperature and pressure and normal boiling point (P = 1 atm.) taken from Woolley et al. (14) are given in Table II.

2. Vapor Pressure

Normal hydrogen

Woolley et al. (14) have developed an equation for the vapor pressure of liquid hydrogen from the triple point to 20.4° K. However, they state that the equation reproduces the experimental vapor pressure measurements of the University of Leiden from 20.4° K to 33.19° K within the limits of experimental accuracy. This equation is

Since this report was completed, an excellent summary of the physical and thermodynamic properties of hydrogen by Scott (37) has been published.
TABLE II
TRIPLE POINT TEMPERATURES AND Pressures AND NORMAL Boeing Points FOR n-H$_2$ AND p-H$_2$

<table>
<thead>
<tr>
<th></th>
<th>Boiling Point $^\circ$ K</th>
<th>Triple Point $^\circ$ K</th>
<th>Pressure (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-H$_2$</td>
<td>20.39</td>
<td>13.96</td>
<td>54.0</td>
</tr>
<tr>
<td>p-H$_2$</td>
<td>20.27</td>
<td>13.81</td>
<td>52.8</td>
</tr>
</tbody>
</table>

$log_{10} P$(mm Hg) = 4.66687 - $\frac{44.2569}{T}$ + 0.020537$T$  (1)

More recently White, Friedman and Johnston (16) have remeasured the vapor pressure of n-H$_2$ from 20.4° to the critical point. The equation has the form

$log_{10} P$(atm.) = $a + \frac{b}{T} + cT + dT^2$  (2)

where

\begin{align*}
a &= 3.068281 \\
b &= -55.25642 \\
c &= -3.1282 \times 10^{-2} \\
d &= 6.6989 \times 10^{-4}
\end{align*}

White et al. (16) have expressed the opinion that their results are more reliable than the earlier data obtained at the University of Leiden because of improved temperature control. Comparison of Equation (2) and Equation (1) made at identical pressures showed that the difference $T_{HJ} - T_{NBS}$ varied approximately linearly with $T$, reaching $+0.18^\circ$ at the critical temperature. Equation (1) is recommended for use below 20.4° K and Equation (2) for use above 20.4° K.

Parahydrogen

The vapor pressure of p-H$_2$ has been measured by Hoge and Arnold (27) from the normal boiling point to the critical point. Their experimental results were expressed in the form of a table permitting linear interpolation except above 50° K. The vapor pressure of p-H$_2$ from the triple point to the normal boiling point has been expressed by Woolley et al. (14) in Equation (3)

$log_{10} P$(mm Hg) = 4.64392 - $\frac{44.3450}{T}$ + 0.02093$T$  (3)

S. Saturated Liquid and Vapor Density

Normal Hydrogen

Mathias, Crommelin and Onnes (30) and Onnes and Crommelin (28) have measured the saturated vapor and liquid densities of hydrogen from the triple point to very near to the critical point. Their temperature data have been
corrected to an ice-point of 273.16° K by multiplying by the factor 273.16/273.09. The densities as well as the molal volumes are shown in Table III. Woolley et al. (14) have used the data of Scott and Brickwedde (29) below 20° K and the data of Mathias et al. (30) above 20° K to obtain the smoothed values also shown in Table III. The values below 20.39° K were calculated from their equation

\[
V(\text{cm}^3 \text{ mole}^{-1}) = 24.747 - 0.08005 T + 0.012716 T^2
\]  

White et al. (16) have remarked that the vapor density data of Mathias, Crommelin and Onnes (30) agree with vapor density data obtained in their laboratory above 20° K.

**TABLE III**

SATURATED LIQUID AND VAPOR DENSITY FOR n-H₂

<table>
<thead>
<tr>
<th>T (°K)</th>
<th>Density gm./cc x 10²</th>
<th>Molal Volume cc/gm. mole</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Liquid</td>
<td>Vapor</td>
<td></td>
</tr>
<tr>
<td>13.96</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>7.631</td>
<td>0.020</td>
<td></td>
</tr>
<tr>
<td>14.82</td>
<td>7.538</td>
<td>0.031</td>
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<td>15</td>
<td>7.494</td>
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<td>16.34</td>
<td>7.421</td>
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<td>17</td>
<td>7.344</td>
<td>0.064</td>
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</tr>
<tr>
<td>17.10</td>
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<td>17.90</td>
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<td>18</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>7.192</td>
<td>0.101</td>
<td></td>
</tr>
<tr>
<td>19.33</td>
<td>7.137</td>
<td>0.116</td>
<td></td>
</tr>
<tr>
<td>19.85</td>
<td>7.124</td>
<td>0.264</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.39</td>
<td>6.724</td>
<td>0.405</td>
<td></td>
</tr>
<tr>
<td>20.42</td>
<td>6.416</td>
<td>0.613</td>
<td></td>
</tr>
<tr>
<td>20.80</td>
<td>5.740</td>
<td>0.806</td>
<td></td>
</tr>
<tr>
<td>21</td>
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<tr>
<td>21.21</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.31</td>
<td>6.050</td>
<td>1.081</td>
<td></td>
</tr>
<tr>
<td>25.86</td>
<td>5.001</td>
<td>1.366</td>
<td></td>
</tr>
<tr>
<td>27.37</td>
<td>4.316</td>
<td>1.922</td>
<td></td>
</tr>
<tr>
<td>30</td>
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<td>30.07</td>
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<td></td>
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</tr>
<tr>
<td>32.53</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>33.19</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

WADC TN 59-230 -22-
Parahydrogen

The only density measurements for saturated liquid p-H$_2$ appear to be those of Scott and Brickwedde (29) for the range 14 to 20° K. Woolley et al. (14) have presented values of the molal volume of p-H$_2$ at even temperatures which are reproduced in Table IV. These values have been calculated from their equation

$$V(\text{cm}^3 \text{ mole}^{-1}) = 24.902 - 0.0888 T + 0.013104 T^2$$

(5)

No data for the saturated vapor appear to exist.

**TABLE IV**

<table>
<thead>
<tr>
<th>Molal Volume of Saturated Liquid p-H$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>26.176</td>
</tr>
<tr>
<td>26.227</td>
</tr>
<tr>
<td>26.518</td>
</tr>
<tr>
<td>26.836</td>
</tr>
<tr>
<td>27.179</td>
</tr>
<tr>
<td>27.549</td>
</tr>
<tr>
<td>27.945</td>
</tr>
<tr>
<td>28.368</td>
</tr>
</tbody>
</table>

4. Heat of Vaporization

**Normal Hydrogen**

White et al. (16) have used their vapor pressure equation (Eq. 2), the saturated vapor and liquid densities of Mathias, Crommelin and Onnes (30) and the Clapeyron equation to compute the heat of vaporization as a function of temperature. Their calculated values are shown in Table V.

5. P-V-T Relations for Liquid Hydrogen at Elevated Pressures

**Normal Hydrogen**

Johnston, Keller and Friedman (17) have made extensive measurements of the compressibility of liquid n-H$_2$ over the pressure range 9 to approximately 100 atm. from 20° to the critical point. Since no measurements were made below 9 atm. Johnston et al. used the saturated density data of Mathias et al (30) to extend their data to the saturation curve. White and Johnston (18) have extrapolated
Table V
HEAT OF VAPORIZATION OF n-H₂

<table>
<thead>
<tr>
<th>Temp.</th>
<th>ΔHᵥ</th>
<th>Temp.</th>
<th>ΔHᵥ</th>
</tr>
</thead>
<tbody>
<tr>
<td>° K</td>
<td>cal./mole</td>
<td>° K</td>
<td>cal./mole</td>
</tr>
<tr>
<td>20.40</td>
<td>218.7</td>
<td>31.0</td>
<td>129.8</td>
</tr>
<tr>
<td>22.0</td>
<td>212.7</td>
<td>32.0</td>
<td>102.2</td>
</tr>
<tr>
<td>24.0</td>
<td>203.0</td>
<td>32.5</td>
<td>80.6</td>
</tr>
<tr>
<td>26.0</td>
<td>190.7</td>
<td>32.75</td>
<td>65.5</td>
</tr>
<tr>
<td>28.0</td>
<td>173.6</td>
<td>33.0</td>
<td>40.3</td>
</tr>
<tr>
<td>29.0</td>
<td>162.3</td>
<td>33.1</td>
<td>30.2</td>
</tr>
<tr>
<td>30.0</td>
<td>148.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

these volume data to 150 atm. and have used their smoothed P-V-T data to calculate the thermodynamic properties of the liquid relative to the properties of the saturated liquid.

More recently Stewart (31) has re-examined the data of Johnston (17, 18) and Mathias (30) with a view to preparing a P-V-T diagram in the form of isometrics. He has concluded that the data of Johnston do not extrapolate smoothly to the saturated liquid density data of Mathias, suggesting that one or the other set of data may be somewhat in error. The discrepancies in the molal volumes are small, however, amounting to less than one per cent for all temperatures below 32° K.

Parahydrogen

No P-V-T data for liquid p-H₂ at elevated pressures appear to be available.

6. P-V-T Relations for Gaseous Hydrogen at Low Temperatures

Normal Hydrogen

Woolley, Scott and Brickwedde (14) have examined critically the P-V-T data for gaseous n-H₂ available up to 1946. Most of these data resulted from the work of investigators at the University of Leiden. More recently Johnston and coworkers (19, 20, 21, 22) at the Ohio State University have made extensive measurements of the P-V-T relations for n-H₂ which have added greatly to the data, especially below about 50° K where the Leiden data were rather sparse. No critical evaluation of the relation between these newer data and the conclusions of Woolley et al (14) has appeared. Ziegler (32) has compared several of the Leiden and Johnston isotherms in the region 20-60° K. For the most part the compressibility factor Z(Z = pv/RT) differs by less than one per cent. However, at 33° K discrepancies as large as 1.85 per cent were noted.
Parahydrogen

No P-V-T data for gaseous p-H$_2$ at low temperatures appear to be available.

7. Heat Capacity of Gaseous and Liquid Hydrogen

Gaseous Hydrogen

Woolley et al. (14) have computed the heat capacity of p-H$_2$, o-H$_2$ and n-H$_2$ in the gaseous state over a wide range of temperature. Their values for C$_p^o$ are given in Table VI.

<table>
<thead>
<tr>
<th>Table VI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HEAT CAPACITY, C$_p^o$ (cal/gm mole °K), OF p-H$_2$, o-H$_2$ AND n-H$_2$</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>T °K</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>33.1</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>50</td>
</tr>
</tbody>
</table>

The heat capacity C$_p^o$ of n-H$_2$ gas as a function of pressure can be computed from the P-V-T relations given by Woolley et al. (14). The corresponding values for p-H$_2$ should be very nearly the same as for n-H$_2$ over the range 10-50° K since C$_p^o$ is almost the same for both gases and the P-V-T relations for p-H$_2$ are probably very similar to those for n-H$_2$.

Johnston and coworkers (23) have used their extensive P-V-T measurements for gaseous n-H$_2$ to compute (C$_p$ - C$_p^o$) over the range 20° - 300° K for pressures from zero to 200 atm. For temperatures less than 50° K the values of (C$_p$ - C$_p^o$) computed by these investigators probably are not reliable at the higher pressures. Thus, for T < approx. 42° K, (C$_p$ - C$_p^o$) becomes negative for pressures.
greater than 40-60 atm. The trouble appears to arise from the difficulty of fitting the experimental P-V-T data with a virial-type equation (23, 20, 32) at these low temperatures.

**Liquid Hydrogen**

**Normal Hydrogen**

Woolley et al. (14) have summarized the heat capacity of the saturated liquid, Cₗ, over the range 14° - 20° K. No measurements for n-H₂ above about 22° K appear to have been made.

**Parahydrogen**

Johnston and his coworkers have measured Cₗ for liquid p-H₂ over the range 14° - 20.3° K (25) and from 18.28° to 31.49° K (24). The agreement between the values of Cₗ found by Johnston for p-H₂ and those given by Woolley et al. (14) for n-H₂ over the range 14° - 20° K is very good. In the absence of Cₗ data for n-H₂ above 20° K, it seems reasonable to use these data of Johnston et al. for p-H₂.

8. Miscellaneous Properties

The material in this section does not represent an exhaustive search of the published literature, and is included primarily to serve as a point of departure for further study.

**Velocity of Sound**

Hilsenrath et al. (33) list a number of references to the velocity of sound in gaseous hydrogen at low temperatures and give limited data for several pressures down to 20° K. Brown (34) has used the equation of state and heat capacity data compiled by Woolley et al. (14) to compute the velocity of sound in gaseous n-H₂ from 26° K to 600° K and for a wide range of pressures. These results have been presented in the form of a chart.

Only limited data are available for the velocity of sound in p-H₂ below 100° K and none appear to be available below 50° K. However, since C₁ is very nearly the same for both n-H₂ and p-H₂ below 50° K and the equations of state may also be expected to differ only slightly it may be assumed that below 50° K the velocity of sound in p-H₂ will be very nearly the same as for n-H₂.

The velocity of sound in liquid n-H₂ has been studied by van Itterbeek and Verhaegen (35).
**Dielectric Constant**

The dielectric constant of liquid n-H$_2$ has been represented by the relation

$$D = 1.296 - 0.00345 T$$

by Chelton and Mann (36) over the range 14-24° K. They state that the original data (See Nat. Bur. Stds. Research Paper 3282) extended over the range 18.723° ≤ T ≤ 20.5° K.

**Viscosity**

Data for the viscosity of gaseous and liquid hydrogen in the range below the critical temperature have been summarized by Woolley et al. (14).

**Thermal Conductivity**

**Gaseous Hydrogen**

The thermal conductivity of gaseous n-H$_2$ at 1 atm. over the range 10° to 600° K has been summarized by Woolley et al. (14) who have also discussed the effect of pressure on thermal conductivity.

**Liquid Hydrogen**

No measurements of the thermal conductivity of liquid hydrogen appear to have been made.†

**Thermodynamic Charts and Tables**

**Normal Hydrogen**

Woolley et al. (14) have prepared extensive tables of (H°-H)/RT and (S°-S)/RT for n-H$_2$ gas based on their analysis of the equation of state data available in 1946. They have used these and other thermal data to construct a complete T-S diagram for the range 14° to 600° K. More recently Johnston and his coworkers (23) have used their newer P-V-T measurements to compute (H°-H), (C_p-C_p°) and (S°-S) for gaseous n-H$_2$ from 20° to 300° K up to 200 atm. Their results are presented in the form of charts and include an H-S diagram for the range 20° to 60° K. Johnston et al. did not discuss the relation of their work to that of Woolley et al. or others. In view of the difficulty of fitting the virial form of the equation of state to their data below about 40° K (see comments in Section 6) it is felt that their computed thermodynamic quantities should be used with caution below 40° K.

†Since this report was completed, an excellent summary of the physical and thermodynamic properties of hydrogen by Scott (37) has been published in which the thermal conductivity of liquid n-H$_2$ from 16° to 30° K is summarized, based on the measurements of Mattox, Powers and Johnston (38).
Johnston et al. (18) have used their P-V-T data for normal liquid hydrogen to compute \((S-S_s), (H-H_s)\) and \((C_p-C_{ps})\) (where the subscript "s" refers to saturated liquid) for liquid \(n-H_2\) at one degree intervals from 20° to 33° K up to 150 atm.

**Parahydrogen**

No similar thermodynamic charts or tables appear to have been prepared for \(p-H_2\).
Appendix B

Supplementary Review of the Literature
on Two-Phase (Gas-Liquid) Fluid Flow in Pipes
This bibliography extends and brings up to date the report, Review of the Literature on Two-Phase (Gas-Liquid) Fluid Flow in Pipes, by William A. Gresham, Jr., Perry A. Foster, Jr., and Robert J. Kyle, Wright Air Development Center Technical Report 55-422 published June 30, 1955. It is also identified as Georgia Institute of Technology, Engineering Experiment Station Interim Report No. 1, Project No. A-186, and is available from ASTIA as AD 95752. The bibliography has been extended to include material published through August, 1959. Some references previous to 1955 have been included which were not cited in the original bibliography.

The bibliography lists all material known to the editors on simultaneous flow of liquid and gas through pipes, tubing, and closed channels. Circulation in steam boiler tubes, discharge of saturated fluids through nozzles and orifices, transfer of liquid sprays through pipes, and flow of liquid films in closed conduits, are all related topics which are included.

Sources of information included the following abstracting journals:

- Applied Mechanics Reviews
- Battelle Technical Review
- Chemical Abstracts
- Dissertation Abstracts
- Engineering Index
- Fuel Abstracts
- Nuclear Science Abstracts
- Rheology Abstracts

In addition, the files of the Armed Services Technical Information Agency on the subjects of Fluid Mechanics, Chemical Engineering, Liquid Fuels, and Instrumentation, were searched for pertinent material. Cross references provided much valuable material, particularly in the case of foreign sources. Another source of information was direct correspondence with thirty-eight U. S. and foreign universities which reported research work on two-phase fluid flow at the time of preparation of the earlier bibliography.

The nomenclature employed in the abstracts of this bibliography is that of the original authors, and bears no relation to the nomenclature of this report as listed on pp. vi-vii. There is not necessarily any consistency of terminology or symbols among the 393 references, or between them and this report.

An instrument is described which utilizes a scanning technique to count and classify spray droplet images. Light pulses of various durations are converted into electrical pulses and fed into electronic sorter-counter circuits which classify the chords into 15 size classes.


The flow of a flashing mixture of water and steam through smooth annuli of fine clearance has been investigated experimentally. Test data have been obtained with inlet conditions of 600°F and 3,000 psig. Critical conditions have been observed experimentally up to these temperatures and pressures. With the assumption that the flashing mixture is homogeneous a method for the prediction of flow and two-phase pressure drop is presented and discussed. (Chem. Abst. 52, 4667, 1958.)


Heat transfer data were taken for methanol and freon-12 condensing inside a horizontal tube over considerable ranges of pressure, temperature driving force, liquid loading, and vapor velocity. For condensation in a horizontal tube, three primary regions of flow are postulated: (1) semi-stratified flow (annular condensation and run-down superimposed on stratified flow), (2) laminar annular flow, and (3) turbulent annular flow. A semi-theoretical equation is developed and shown to be applicable to both semi-stratified and laminar annular flow. Other equations must be used for turbulent annular flow.


Deposition rates of small water droplets (average diameter 27μ), from a turbulent air stream onto the walls of a straight duct, were measured. The major resistance to transfer from the air stream to the duct wall, as deduced from the shapes of the radial profiles of mass velocity of suspended matter, resided in a relatively thin layer of gas adjacent to the wall. This hypothesis led to the relation, Kg = 0.00335 u1.17, for the film coefficient u being the velocity. The coefficient was found to be from 10 to 20 times greater, on a mass basis, than estimated coefficients for NH3 and CO2 under comparable conditions. (Chem. Abst. 51, 7628f, 1957.)


Studies are made of heat transfer from surfaces of heated metal rods during the cross-sections flow of air containing minute droplets of water. Results
showed the appearance of two states of transfer depending on the temperature of streamlined surface. Quantitative data are obtained for each state in condition of slow air flow. (Nucl. Sci. Abst. 11, 25, 1957.)

6. W. F. Allen, Jr., "How to Size Piping and Valves for Flashing Mixtures." Power Eng. 56, No. 5, 60; No. 6, 83; No. 8, 85 (1952).

Flashing mixtures of water and steam cause erosion in piping and valves, reduced flow capacity and the like. This article gives formulas for figuring pipe and valve sizes to minimize these troubles, compares test and calculated data for specific installations, and shows numerical calculation for case in which flashing may be eliminated.


Local heat transfer coefficients and pressure drop were determined for Refrigerant-22 condensing in an 8 ft. long, 3/4-in. inside diameter horizontal tube. The method of Carpenter and Colburn was used to correlate the data and an empirical correction factor was derived that enabled the data in the desuperheating region to also be correlated by this simplified method. The analyses of Seban and Rohsenow were modified to include the effect of high vapor shear in horizontal tubes. This theoretical approach is well supported by the experimental data when the method of Martinelli-Nelson is employed to compute the shear stress at the tube wall.


The investigation was undertaken to provide basic data on flow pattern, pressure drop and liquid holdup for the flow of liquid-gas mixtures in a 1-in. cocurrent pipeline contactor. Descriptions of the various possible flow patterns are presented. Visual observations were made of most of these patterns in the straight pipe and a return bend, and photographs of typical flow patterns are given. The pressure drop for the straight pipe and the holdup data were compared with those given in the published literature. Pressure-drop data for the flow of liquid gas mixtures have been extended to include the return bends and the inlet mixing tee.


A comparison of the flow patterns presented by the various authors has been made. This comparison indicates good agreement considering that the transitions between flow patterns are vague and were detected visually. The following general flow patterns were found to occur as the gas phase is present in increasing quantities: (1) pure liquid, (2) bubble flow, (3) plug flow, (4) stratified flow, (5) wavy flow, (6) slug flow, (7) annular flow, (8) mist or spray flow, and (9) pure gas. Some of the flow...
patterns were not stable and tended to change with time and distance. With two-phase flow of a single component (e.g., water and steam) the slip ratio must be known to permit calculations from a temperature or pressure. Fifteen references are given.


The circulation of water in boiler tubes at high pressures is a complex subject and most of the theories are based on the supposition that the vapor-water mixture in a boiler behaves as a homogeneous fluid; a convenient theory, but one which has some objectionable features. A series of experiments has been performed with 2.54 cm. diameter tubes at pressures approaching 210 kg./cm.², and other experiments on larger, different tubes are in progress. The apparent density of the vapor-water is measured by the use of x-rays from a cesium source. (*Nucl. Sci. Abst.* 11, 1235, 1957.)


Describes apparatus and preliminary tests for a new research project at Cambridge University. The project will study fundamentals of flow during vaporization as a preliminary to understanding boiler circulation.


Calculation of the coil centrifugal rectification apparatus is given. The calculation is based on the Gel'perin-Pebalek equation for binary mixtures with close boiling points of their components. The introduction of the Reynolds no. for the liquid phase makes the calculation more accurate. For this purpose a calculation of the change of the average liquid rate along the channel is given. (*Chem. Abst.* 53, 7685d, 1959.)


For the pressure drop calculation of the mist range the Fanning equation may be used if the mist is considered homogeneous, so that liquid particles acquire almost the same velocity as the vapour. The pressure drop calculation for the foam range, which follows after the liquid range is shown not to be of importance.


Five stages of operation with increasing ΔT can be distinguished: simple sensible heat exchange, slow simmering, ejection of slugs of liquid and puffs of steam, emission of a crown of slow-moving drops of liquid with a jet of steam containing entrained liquid occupying the core of the tube, and production of a stream of steam containing a suspension of fine particles of liquid traveling at high speed. Everything else being equal, the heat-transfer coefficients in the boiling section of the tube are greater
at smaller temperature drops. It would appear more important to drown the heating surface with relatively large amounts of liquid than to depend on high velocity to wipe off the steam bubbles. The relationships between length of tube, $\Delta T$, length of boiling section and coefficient of heat transfer are still not adequately determined, and exact statements as to the ranges in which the important last three stages occur cannot yet be made (Chem. Abst. 34, 26539, 1940.)


This paper discusses the nature of the flow of saturated and nearly saturated water into regions where the pressure is less than the saturation pressure. It presents a method of computing the mass rate flow through orifices and nozzles which is based on the ratio of evaporation from a metastable liquid core into a surrounding ring of vapor. The flow rates for orifices are predicted accurately and rates for nozzles are predicted to within 10%. The analysis is restricted to adiabatic flow conditions.


The designs and analyses of many operations involving interaction between liquid and gaseous systems suffer from a lack of information of the gas throughput versus gas hold-up in the system. For the gas throughput versus gas hold-up in vertical pipes the following data and analyses are presented: Experimental data in non-circulation systems to show the effect of pipe size and the effect of the physical properties of the gas and liquid; experimental data in non-circulating systems for the average fluctuation of the gas hold-up in circulating systems (both gas and liquid flowing through the pipe); and an experimental confirmation of the utility of an analytical model. (Nucl. Sci. Abst. 10, 11, 163, 1956.)


The author reports research on pipeline design for two-phase flow of oil and gas. The data of many investigators is combined with much new data into charts which correlate pressure drop and flow patterns. Methods of calculation and pipeline design are set forth.


This article, chiefly concerned with flow of natural gas, gives representative figures for efficiency loss when liquid is present in gas lines.


A model is proposed for turbulent, cocurrent flow of liquid and gas or vapor through a pipe or channel, which assumes the fluid to be a single phase whose density is a function of radial position. A void fraction radial-distribution equation, based on bubble transport, is derived, but is not presently useful, since bubble radii and diffusivities are not known. Power-law assumptions for the radial-void fraction and velocity distributions are therefore made, which lead directly to an expression for the mean void fraction as a function of the quality. The wall stress is then computed, assuming that the Blasius expression is applicable. Good agreement with the Martinelli-Nelson correlation for steam-water void fractions and frictional pressure drops over a range of pressures from 100 to 2500 psia and void fractions from 0 to 0.80 - 0.85 is obtained by choosing a single value of the flow parameter K. More generally, however, K is a function of pressure, quality, and mass velocity. As an example of the use of the first-order terms in the Taylor expansion of K about a reference condition, the wall shear-stress equation is applied to boiling-water data taken at various mass velocities. Some hitherto undiscovered factors which may affect the void-fraction and shear-stress correlations are pointed out.


The author's observations of two-phase flow patterns are among the earliest recorded. He observed bubble flow forming in the bottom of evaporator tubes, the bubbles growing in size until plug flow, annular flow and finally spray flow are achieved.


In liquid-type homogeneous reactors, bubbles of gas are formed as a result of fissions and radiation. The loop separator consists essentially of a single coil of pipe, or tubing inserted into the fuel stream. In passing through the loop, a mixture of gas and liquid will be acted upon by centrifugal forces which concentrate the gas on the inner surface of the loop. Extraction taps located on this inner surface permit removal of this gas layer. (Nucl. Sci. Abstr. 13, 13,046, 1959.)


The results of an experimental investigation of the isothermal flow of water-air mixtures are discussed. The investigation was undertaken to determine the effect of surface tension on the pressure drop of a two-phase system flowing in a horizontal tube. The pressure drop data compared with data given in the published literature on the two-phase flow
of fluids. Restrictions imposed during the investigation were: both phases in turbulent isothermal flow, no mass transfer or heat transfer between phases, surface tension values between 34 dynes/cm. and 74 dynes/cm., one test section of 1-in. clear plastic pipe was used, vapor to liquid ratio limited to values between 2 and 16 approximately (based on average temperature and pressure in pipe). Two conclusions are drawn, viz: the variation of surface tension of the liquid phase had no effect on the pressure drop within the limitations of the experiment; the data obtained in this investigation are in reasonable agreement with other published correlations.


A procedure is given for simplifying the use of the theoretical energy equation for predicting pressure losses in two-phase pipe line flow. An empirically derived relationship linking density, velocity and pipe size with friction factor is presented, which is analogous with the relationship for single phase flow and which is believed to apply to turbulent flow conditions regardless of crude characteristics. (Fuel Abstr. 18, 3150, 1955.)


A procedure for a stepwise trial-and-error method of obtaining pressure drops in a two-phase water-steam system is described using the Martinelli-Nelson equations for stratified flow. The procedure may be applied to the prediction of pressure drops in nuclear reactors with boiling coolant and in steam boilers, evaporators, and condensate return lines. A nomograph for steam qualities up to 25% and over the temperature range 170 to 350° F for rapid evaluation of two-phase acceleration pressure drop and a chart for rapid computation of the Lockhart and Martinelli empirical parameters $X_{tt}$ are
presented. This parameter for two-phase flow equals the square root of the ratio of liquid friction drop, assuming each phase flowing alone. The subscript "tt" presumes that both the liquid and the vapor in the flowing two-phase fluid are in turbulent flow. (Nucl. Sci. Abst. 8, 1954.)


The characteristics of flow of liquid-gas mixtures in large pumps and vertical-tube boilers are explained by resolving the velocity with which bubbles move through the tube into its two components. The origin and behavior of these components are described. (Nucl. Sci. Abst. 8, 1954.)


This early study of vertical boiling systems demonstrates that the relative velocity of two phases decreases with increasing pressure.


A method is described to measure the total water flowing in a steel pipe, its position, the shape of its profile, the distribution of water in continuous flow or droplets. The determination of these factors by absorption measurements of β or γ radiation were carried out. A detector and source, diometrically opposite each other and mounted on a rotatable holder around the pipe, will give a minimum count rate for the position occupied by the water and its profile in two-phase flow. Sr$^{90}$/Y$^{90}$ was chosen as the source of β rays and Sb$^{125}$ as that for γ rays. Effective water thickness, ranging from the pipe full of water to that of a thickness of 0.002 in. were measured. (Chem. Abst. 50, 8105d, 1956.)


A copper and glass test section has been constructed to enable the correlation of film boiling coefficients with visually or photographically observed liquid-vapor flow phenomena during boiling in vertical tubes. The equipment has been tested and proven operable. In a single run a peak boiling film coefficient of 8,200 Btu/hr., ft.$^2$ was obtained. Edgerton photographs of the effluent stream under various flow conditions are shown.


This paper correlates information on gas lifts to flow through the tubing-casing annulus, and presents a procedure for the design of such a system.

In this paper are presented the results of tests to determine the flow characteristics for saturated water and for various mixtures of saturated water and steam through sharp-edged thin-plate orifices. Tests show that the actual flow of saturated water through these orifices is considerably greater than would be expected from theoretical calculation based upon a change of state and that no critical back-pressure condition is evident. Primarily, this investigation was intended to determine the feasibility of using throttling orifices alone or in combination with float-operated drainers for regulating the draining of condensate from feedwater heaters. These test data apply only to throttling orifices and should not be used to design orifices for metering purposes. An Appendix to the paper shows the application of the formulas to the design of a single-stage orifice to drain the condensate from a feedwater heater, and to the design of an orifice to be used in series with a float-operated drainer.


A review is presented of the published literature (approximately to Dec. 1957) concerning the hydrodynamics of two-phase gas-liquid flow with regard to the methods and accuracy of predicting pressure drop, liquid hold-up, etc. Particular emphasis was placed on the annular flow pattern. There are 113 references included. (Nucl. Sci. Abst. 12, 1471, 1958.)


In this paper the dimensionless dependences for the coefficients of heat transfer data and mass transfer data under the joint action of heat and mass transport in a heterogeneous system with separation surface impenetrable for the inert component of the binary gaseous or vapor-gas mixture, are studied in their general form.


This article presents a simple, accurate method for predicting pressure drop for two-phase fluid in horizontal pipes. The method has been reduced to a simplified graphical procedure suitable for field use. 25 references. (Battelle Technical Review 5, 4124, 1956.)


Studies are reported of subcooling of a cryogenic fluid by cavitation with a reciprocating disk, and of the behavior of such a fluid in a glass-cylinder pump, aided in the design of a 5-cylinder, 240-rpm submerged-piston pump capable of delivering 55 gallons/min. of boiling H at 155 lb./sq. in. discharge pressure. Complete pump design specifications are given. (Chem. Abst. 53, 11,901c, 1959.)


The results of an investigation on the effect of motion of the liquid on the heat exchange coefficient, when it boils in an inclined tube, are described. Figures are given to show the heat exchange coefficient as a function of the circulation rate \( \alpha_2 = \alpha_2(w) \) for various values of the pressure and the specific thermal load. It is shown that \( \alpha_2 \) is a linear function of the circulation rate, in the range of this parameter investigated, which can be represented by \( \alpha_2 = C_0 + C_1w \), thus refining the empirical formulæ. Some considerations are given regarding the mechanism of the heat exchange process when the circulating liquid boils in tubes, and a general criterion is proposed for this form of heat exchange.


The results are given of an investigation of useful pressures developed by the vapor-fluid mixture of an organic heat-carrier at natural circulation in a 56 to 70 mm. tube. (Nucl. Sci. Abst. 681, 1957.)


Temperature profiles were determined along the single heated horizontal tube of a closed circuit loop with a mixture of diphenyl and diphenyl oxide, which was inside the tube heated by hot flue gases. For pressures varying from 2.5 to 10.2 atm. (abs.), circulation velocities of 0.3 to 0.7 m./sec., reduced vapor velocity from 0 to 7 m./sec., and with thermal flux ranging from 10,000 to 60,000 kcal./m.² hour, it was found that two-phase flow existed in the tube and that the wall temperature in the upper part of the tube exceeded 400° C, i.e., was above the decomposition temperature. A residue containing decomposed mixture and hydrated Fe oxides was deposited on the inside upper pipe surface; with continued operation hot-spot formation is expected. (Chem. Abst. 48, 6a, 1954.)


The hydrodynamic conditions of operation of gas lifts, which can be used as high-intensity apparatus for absorption of gases by liquids, were studied.
The factors of turbulence of the flow at various ratios of gas to liquid consumption were investigated. It was found that the curve of the dependence of liquid consumption on gas consumption at constant depth of immersion, increasing at first, passes through a maximum, then, decreasing, goes through a minimum after which it increases linearly without limit. It is indicated that the maximum consumption of liquid depends on the depth of immersion and on the viscosity of the liquid, and is practically independent of gas consumption. The form of the nozzle and the linear velocity of the gas emerging from the nozzle do not influence the consumption of gas and the hydraulic process of operation of the apparatus. (Chem. Abst. 53, 12,764f, 1959.)


Study of the flow of refrigerant through a capillary tube is amenable to the methods of compressible fluid flow. For adiabatic flow through a given tube with a given inlet pressure and temperature there will exist a critical pressure just before the tube outlet, below which the pressure cannot fall. Variations of evaporator pressure below this critical pressure will not affect the flow rate through the tube. For the adiabatic case, the inlet temperature and pressures and the oil content of the refrigerant determine the flow rate. The presence of some oil in the liquid refrigerant increases the flow rate by depressing the boiling pressure of the refrigerant, thus maintaining the flow in a liquid state in a greater portion of the tube. It is possible to develop a curve, the area under which is equal to the tube length required for a given flow rate and set of inlet conditions.


Presented here are the experimental results of a test program on capillary tube expansion devices using heat exchangers. A parameter called the bubble point temperature, is used which simplifies the study of the nonadiabatic flow through the tube. Flow relations are given for different bore-length combinations at several different inlet pressures using the bubble point temperature concept. A set of sample calculations shows the methods of solving for friction factors for both single phase and two phase flow.


The integral $\int dp/V$ for isenthalpic expansions is evaluated for initial saturation pressures up to 600 psia.


This paper is a study of effect of up and down hill flow on pressure drop; recent field results show that excessive pressure drops have been encountered in two-phase pipe lines through hilly country; tests were made with oil, water and air. (Engineering Index 431(2), 1958.)

The flow of water spray from evaporator tubes is observed and discussed.


A direct theoretical analysis was undertaken of upward annular two-phase flow; inadequacies in experimental correlations indicate that the present theoretical models are either in error or are incomplete. Application was made of modern knowledge in the fields of boundary layer theory and film condensation. It was established that correlations and analytical methods that superimpose force fields such as that of gravity on the flow result in unrealistic patterns for flow distribution, fluid shear and local pressure drop. Success with such methods may be attributed to grossly compensating errors. The analysis was carried to the point of determination of the interface wave phenomenon. A further program of investigation of wave phenomenon for the inclinations from horizontal to vertical is recommended. (Nucl. Sci. Abstr. 13, 423, 1959.)


Experiments were conducted for investigating heat transfer and pressure drop phenomena in a forced circulation water system at elevated pressures. Heat transfer duct pressure loss is presented as a function of heat flux density for fluid pressures between 100 and 2500 psia.


A high pressure, circulating flow system with an electrically heated heat transfer tube was used to obtain heat transfer, pressure drop, and density data, with and without surface boiling, and to determine conditions for inception of boiling and for tube burnout. The range of variables covered by earlier investigators was extended to include pressures up to 2500 psia, fluid temperatures up to 650° F, and heat flux densities up to $3.8 \times 10^6$ Btu/hr., ft.$^2$


Measurements are correlated on the assumption that no vaporization occurs in the nozzle throat until throat pressure fell to two-thirds the initial pressure. The explanation advanced is that the liquid must be superheated before the internal pressure can overcome the surface tension of the minimum size bubble.
Two-phase fluid flow is distinguished from single-phase flow in two respects: (1) the cross section for flow of either fluid is not defined by the conduit alone and (2) not only the extent but the manner of frictional energy exchange for each fluid depends on the individual rate of flow for both fluids. It was believed therefore that an empirical approach would not adequately describe the various situations encountered in two-phase flow, and so study was undertaken to obtain some understanding of the mechanisms of the flow of liquid with a free surface and the momentum exchange between fluids at that surface. It resulted in the development of a method of predicting liquid holdup and pressure drop for flowing systems in which the liquid, lifted by the gas flowing as a central core moves upward as an annular film along the pipe wall. In order to clarify the relationship of annular flow to the entire range of vertical two-phase flow is presented, followed by an analysis of the special case of vertical, upward, annular flow; a description of the experimental work; and a comparison of experimental data with predictions.

(Chem. Abst. 49, 6663f, 1955.)

An investigation of the operation of air lifts was made to develop feasibility of application to nuclear fuel processing facilities. The effect of the following variables on lift capacity was studied: pipe diameter, submergence ratio, liquid density, liquid temperature, nozzle design, nozzle holder design, eductor shape, and viscosity. Three of the variables had major effect; i.e., pipe diameter, submergence ratio, and liquid temperature. The remaining variables had a negligible effect on lift capacity. It was found that the lift capacity increased as the pipe diameter and submergence ratio increased. An increase in liquid temperature increases the lift capacity if the air rate for maximum liquid flow has not been exceeded; otherwise the increased liquid temperature causes a decrease in lift capacity. If the data are plotted using the weight basis for liquid flow there is no effect of liquid density. However, when plotted on the volume basis the lift capacity is seen to vary inversely with the density of the liquid. The nozzle designs used here attempted to vary the size of...
the air bubbles entering the liquid stream. Nozzle design as studied here had no effect on the lift capacity. The flow of liquid from the horizontal run of pipe into the eductor does not have to be relatively smooth. The difference between smooth and turbulent entrance effects is negligible. There were no indications of the nozzle plugging when lifting a hot, concentrated salt solution. Although the effect of viscosity could not be studied independently it can be deduced from the data obtained that viscosity has a negligible effect on lift capacity over the range studied (aqueous salt solution). The air lift pumps in operation during this investigation have proven themselves to be maintenance-free and very dependable.


The basic mechanism of heat transport in a two-phase flow field is studied in a similar manner to that of the momentum transport case by use of the statistical theory of turbulence. The equation governing the temperature field is of the same type as in the momentum transport case. Statistical relations between the properties of the two phases are studied. An idealized case is used as an illustrative example to show the close relationship between temperature fluctuation properties and velocity fluctuation properties. Analysis is made on the heat transfer of a turbulently flowing fluid with suspended solid particles in a closed conduit. The governing equations for the system under consideration are two coupled non-linear equations. Approximations are made for the linearization of the system, and after transformations, the governing equations with their boundary conditions reduce to the Sturm-Liouville type. Computations of the solution are accomplished by the variational aspect of the eigen-value problems and by the application of Ritz method. The final results are compared with existing experimental data and are discussed. (ASTIA Tech. Abst. Bull., U59-16, 4053, Aug. 15, 1959.)


An experimental investigation of annular two-phase flow was conducted in a vertical tube, 2.498-in. diameter and 28-in. long, employing water and air at ambient temperatures and pressures as the liquid and gaseous media respectively. Systematic experiments were conducted for determining the effect of the rates of flow of the air and water upon the mean thickness of the liquid film and the pressure gradient in the gas stream, although the latter were of secondary interest. Photographic records were made from an oscilloscope trace corresponding to the profiles of the gas-liquid interface at selected rates of flow of the two fluid media. A detailed statistical investigation of the relationship between the amplitude of the interfacial waves and their respective frequencies as a function of the rates of flow of the two fluid media was conducted. An analysis of downward, annular, two-phase flow is presented and the results of that analysis are compared graphically with those from the experimental investigations. The results indicate that the amplitudes and frequencies of the interfacial waves are related by definite spectra and that those spectra characterize the structure of the interfacial surface. (ASTIA Tech. Abst. Bull., U59-15, 3724, Aug. 1, 1959.)

This review contains 55 references.


The author's correlation relates the different variables which have apparent effect upon the two-phase flow of fluids in pipelines. Data are presented in a generalized form for easy application in computing pressure drops in two-phase flow. Flow patterns are also considered in the correlation.


This is a study of pressure drop for flow of two-phase mixtures of air and water in 1-1/2-in. and 3-in. pipes. A total of 264 runs are presented for tests covering pressures to 100 psia, liquid rates to 200 gpm, and air rates to 700 scfm; comparison is made with previous results; a new correlation for turbulent two-phase flow is presented. (Engineering Index 381 (1), 1955.)


A correlation for two-phase flow in pipes to 3 in. diameter and pressure to 100 psia is presented. (Chem. Abst. 7517a, 1956.)


Pressure drops have been measured for a wide range of two-phase flow conditions in horizontal pipes. The tests were made in 1-1/2 and 3-in. pipes using air and water at pressures from atmospheric to 100 psia. The data are compared with the Lockhart and Martinelli correlation. Best agreement is found for performance at atmospheric pressure. The largest deviations are for data taken at 100 psia in the 3-in. pipe. In this case, the predicted pressure drop is higher than the observed by a factor ranging from 1.4 to 2.5. The test results were used to develop an improved correlation for turbulent two-phase flow in horizontal pipes. The correlation represents all of the experimental data within plus or minus 50 per cent, and 92 per cent of the data within 35 per cent. The data of many other investigators correlate equally well. The test results for three typical 3-in. fittings show that single-phase friction coefficients can be used satisfactorily in the correlation for predicting the two-phase pressure drop.

In this article are reported results of experiments in which both surfaces of a liquid annulus were heated. The following equations were obtained for the two-phase heat transfer coefficient:

\[ h_{TP} = 2.97 \left( \frac{q}{A} \right)^{0.6} (D_e)^{-0.514} \]

for annular gaps less than 0.1 inch, while for gaps between 0.1 and 0.3 inch,

\[ h_{TP} = 4.22 \left( \frac{q}{A} \right)^{0.6} (D_e)^{-0.154} \]

In both equations \( D_e \) is the equivalent diameter of the annulus in inches. The plotted results are reproduced in "A Review of Two-Phase Heat Transfer," by J. G. Collier, AEC Report AERE-CE/R-2496 (1958).


Reference is made to conditions under which vapor flowing in pipe or channel can be condensed; the condensation zone of condensing vapor is idealized as an interface separating vapor and liquid phases of fluid with concentrated friction, heat removal, and cold liquid injected at the interface. Rankine-Hugoniot relations are obtained including affects of mass, momentum, and energy sources at interface. An explicit approximate solution obtained. (Engineering Index 426 (2), 1958.)


Parameters are developed from theoretical considerations which correlate data for the flow of steam-water mixtures through sharp-edge orifices. Equations are obtained which permit the estimation of flow rates under such conditions. (Chem. Abst. 52, 19,271a, 1958.)


Data are presented for pressure drop and saturation during flow of air-water mixtures in smooth and rough horizontal tubes; improvements in two-phase flow correlations for rough tubes are presented; approximate empirical relationships developed using these improvements correlate majority of data within 15%. (Engineering Index 408 (1), 1957)

Experimental data on films thicknesses is presented in this early study. The flow of water and of a viscous oil were studied on a flat plate. Film thickness was measured by means of micrometers.


The validity of the Nusselt equation for film thickness is demonstrated. Water, molasses, and 25% NaCl solution were the liquids studied. Flow was observed down the outer vertical walls of polished and unpolished steel pipe.


A review is presented of the published literature dealing with heat transfer to two-phase gas-liquid mixtures flowing in vertical and horizontal tubes under natural or forced circulation. Both single component and two component two-phase heat transfer is dealt with. From this analysis of the literature a general appraisal of the mechanisms of heat transfer is made. Special sections include those on the effects of agitation and surface on nucleate boiling. Recommendations for further work on the subject are put forward. (Nucl. Sci. Abst. 12, 2126-7, 1958.)


This work was carried out in order to study primarily the absorption of carbon dioxide in a wetted-wall column using co-current flow. In addition the absorption in counter-current flow was also investigated, and the average thicknesses of the liquid films were measured under the same experimental conditions. It was found that the use of parallel flow greatly increased the operating range possibly before the conditions in the column became unstable, and that it produced appreciably higher transfer coefficients than in the case of counter-current flow. The various mechanisms of transfer present in the falling film were discussed, and it was decided that the flow could be divided into five separate classes of flow, depending on the relative magnitude of the liquid flow rate, the presence of surface disturbances in the film, and the amount of interfacial shear. (Dissertation Abst. 19, 2039, 1959.)
Performance tests have shown that totally submerged gas-lift circulators offer an economic and effective means for achieving mild liquid agitation in large tanks. Riser pipe diameters from 3 to 15 inches and lengths from 3 to 24 feet were investigated. The effects of footpiece design, liquid temperature, liquid specific gravity, and the depth of liquid cover were also studied. Liquid flow was measured by means of instrumentation developed in this work. It is believed that the flow potential in a gas-lift circulator is the result of a reduction in the apparent specific gravity of the liquid. By equating this potential to the flow resistances, a general method for predicting circulator performance has been developed. The recommended operating range is from 400 to 1200 gpm/ft.² In this range, a 10-foot long riser pipe will require from 0.003 to 0.008 cubic feet of motive gas per gallon of cold liquid circulated. In a boiling liquid, the motive gas requirements are decreased by a factor of about five. Satisfactory operation requires that the motive gas must be noncondensable. The advantages of replacing mechanical agitators with gas-lift circulators are discussed.

Boiling density experiments were conducted on 7/16 x 3-11/16-inch channels, two and four feet long at pressures from 164.7 to 614.7 psia, inlet subcoolings up to 20°F and exit steam weight fractions up to 0.15. Power input was varied from 10 to 50 kw/liter for a 5.04 liter coolant volume by resistance heating of 1/16-inch stainless steel plates. High resistivity, demineralized water was used throughout the tests. The steam void fraction was studied rather than density because it is conveniently related to the ratio of steam to liquid velocities (Vg/Vf) and the steam weight fraction (x), which are fundamentally involved in continuity of the two phases. Steam void fraction curves normalized with respect to average void fraction demonstrated that thermal equilibrium did not exist over portions of the channel when inlet liquid temperature was below saturation, although thermal equilibrium was again reestablished at the exit of 48-inch long channels. Data of runs with inlet liquid at saturation temperature, where thermal equilibrium was assured, were studied with analytical models for variation of (Vg/Vf) with length using the normalized void fraction plots. A definite change of (Vg/Vf) with position in the channel was shown to exist, the variation being approximately linear with channel length for runs where inlet liquid was at saturation temperature assuming (Vg/Vf) to be a function of the volume rate of vapor flow and the volume rate of liquid flow. It may be shown that the rate of change of (Vg/Vf) with length is proportional to the rate of vaporization. Experimental data verified this and showed the change of (Vg/Vf) with length approaches zero when the rate of
vaporization approaches zero. Experiments with unheated riser sections also show this to be true. The conclusion was drawn that the change of \( \frac{V_g}{V_f} \) reflects the acceleration required to remove steam formed in the channel. Satisfactory correlations of \( \frac{V_g}{V_f} \) for saturated inlet conditions were found from plots of \( \frac{V_g}{V_f} \) versus volume rate of liquid flow and plots of \( \frac{V_g}{V_f} \) versus the ratio of liquid to vapor fractions. These correlations appeared unsatisfactory, however, for data obtained with inlet liquid below saturation temperature. A general correlation was found for all data by use of an analytical model. Plots derived from the analytical model showed \( \frac{V_g}{V_f} \) to be a function of the rate of vaporization for liquid inlet temperatures below, and at saturation, with a small spread due to effects of per cent of the channel length in boiling \( \frac{L_v}{L} \). Values of \( \frac{V_g}{V_f} \) at exit of a two-foot channel were shown to be the values at the corresponding point of a longer channel, indicating that length of channel is not a prime factor in determining phase velocity relationships. Flow and two-phase pressure drop data were obtained for predicting flow in channels. A correlation of the Martinelli ratio of two-phase friction gradient to single-phase friction gradient with mean steam void fraction was satisfactory for all pressures. (Nucl. Sci. Abst. 11, 473, 1957.)


These authors redeveloped the Nusselt equations for liquid film flow, introducing the concept of interfacial shear. Many experimental points are plotted, and form a straight line on log-log plot of friction factor versus Reynolds number, conforming to the equation \( f = 24/Re \). The equation holds up to \( Re = 2100 \). The authors point out that there is no indication that gas traction at the gas-liquid interface has any effect on flow of the film. However, there was no positive gas motion.


During an emergency fuel dump from the Pennsylvania Advanced Reactor, the slurry will flash into a vapor-liquid mixture. Design calculations for the emergency drain system will thus require a calculational method for two-phase flow and pressure drop. A literature survey revealed two such methods, a homogeneous method and the Martinelli method. These two methods are described and discussed. The homogeneous method appears most promising for PAR conditions. (Nucl. Sci. Abst. 12, 8089, 1958.)


An accurate method of determining average density and static pressure drop due to liquid acceleration during boiling of subcooled liquids has been
devised and employed in the tests reported in this paper. The effects of system parameters and geometry on average density and acceleration pressure drop caused by vapor formation is proposed. The method relies on photographic data and appears to be valid only to the point at which bubbles coalesce to form vapor clots. It is also indicated that the most severe effects of vapor formations occur if vapor clotting takes place.


The author points out that slip between steam and water phases may affect the predicted steam production. Equations are presented which include a slip factor, sigma.


This paper describes an experimental investigation of forced-convection heat transfer to liquid nitrogen. Data are presented for nitrogen flowing at 40 fps through an annular passage under nonboiling, nucleate boiling, and film boiling conditions at pressures above and below critical.


A tabulation of burnout heat flux data for water under forced circulation conditions and at pressures above 500 psia is presented, which includes all relevant data available from U. S. Government laboratories. New correlation equations for round and rectangular channels are presented. These correlate burnout conditions as functions of several system variables. (Chem. Abstr. 53, 13,6901, 1959.)


Flow patterns similar to those generally found for air-water mixtures were observed in the vertical flow of steam and water. The bubble and plug flow patterns do not exist above 0.2 weight per cent steam.

In order to explain the observed decrease in heat transfer coefficient with increased pressure vaporization, the authors concluded that the specific vapor volume, and hence the velocity of the mixture, are decreased. The equation

\[ \frac{h_{TP}}{h_1} = 3.5 \left( X_{tt} \right)^{-0.5} \]

where \( h_{TP} \) is the two-phase heat transfer coefficient, was found to correlate 85 per cent of the data. The parameter \( X_{tt} \) is defined by

\[ \frac{1}{X_{tt}} = \left( \frac{x}{1-x} \right)^{0.9} \left( \frac{V}{V_L} \right)^{0.5} \left( \frac{\mu}{\mu_L} \right)^{0.1} \]

where \( x \) is quality, \( V \) is specific volume, and \( \mu \) is viscosity. This equation, a strong function of quality, introduces by means of the specific volume terms a correction for the effect of pressure, when nucleate boiling is believed suppressed. The value of \( h_1 \) is found by the Dittus-Boelter equation for the total mass flow.


An instrument employing gamma-ray absorption techniques has been developed for measuring the steam-water ratio in a thick walled steel tube. The instrument was developed to enable this measurement to be made during heat transfer tests on an evaporator in which heat was transferred from sodium to high pressure water. The method depends on the change with steam contents in the amount of absorption of soft gamma radiation passing through the tube. The limitations are examined and an instrument is described applying the method to estimate the steam content in the water flow in a 3/4-in. nominal bore mild steel tube. The instrument is calibrated up to 2.5% steam by weight, the useful range in its present use, but methods of improving the performance are described and recommendations made. (Nucl. Sci. Abst. 11, 6783, 1957.)


Eddy diffusion of mass (water vapor) and momentum was investigated in a wetted-wall channel in which the rippling of the liquid film was eliminated. The measurements of the turbulent exchange coefficients for mass and momentum transport were carried out in a turbulent flow of air within the range of Reynolds numbers of 8,000 to 160,000. A correlation with Reynolds number revealed an approximate linear relation of the eddy diffusivities to Reynolds number. (Chem. Abstr. 52, 15,973a, 1958.)

A study of pressure drop for horizontal crossflow of two-phase gas liquid mixtures through four tube banks, with horizontal tubes is presented; two tube banks have staggered-tube layouts, 60° and 45°; two have in-line or 90° tube-field layouts. Test systems studied were air-water and pentane vapor-pentane liquid. A pressure drop correlation is developed for horizontal two-phase crossflow through tube banks. (Engineering Index, 431 (2), 1958.)


Equations are given for calculating the pressure drop for vaporizing fluids in fired heaters in the absence and presence of steam. (Chem. Abst. 53, 5769g, 1959.)


By use of the von Karman velocity distribution theory new equations are developed which relate liquid-film thickness in concurrent gas-liquid flow to the flow rates, physical properties of the fluids, and to the energy loss. For the case of no gas flowing, the equations reduce to give the film thickness as a function of flow rate and physical properties over the complete viscous to turbulent flow range. The transition from laminar to turbulent flow occurs at a Reynolds number of 1080. Equipment is described for the measurement of liquid-film thickness and wave profile based on a capacitance technique and this equipment is capable of measuring film thicknesses to an accuracy of 0.001 inch. (Chem. Abst. 47, 356h, 1953.)


Experiments on pressure drop of condensing steam in horizontal pipes were conducted, and a new equation developed for computing this pressure drop.


A plot of volume versus entropy for water was prepared, to facilitate evaluations of properties of flashing water at relatively low pressures.

An experimental program was conducted to study the formation and distribution of vapor in a rectangular channel under boiling-heat-flux conditions at 2000 psia. In addition, the problem of preferential distributions was studied to determine its effect on the validity of the results of this program. Over the range of variables tested, there was no flow-rate effect, and the slip, where determinable, appeared to be constant. The void fraction is correlated with the quality and heat flux, in the vicinity of zero quality; the dependence upon heat flux decreases with increasing quality in this region. Inlet-temperature variation has no effect on the value of the void, providing the inlet temperature is below the temperature necessary for local boiling. (Nucl. Sci. Abst. 11, 680, 1957.)


The problem is analyzed in analogy with that of sediment transport and is partially solved. While it has not been possible as yet to predict the air content of the mixture for a given state of flow or of turbulence, the vertical distribution of air in a turbulent water mass was found to follow the laws of suspension. The change of the average flow velocity and flow depth of an open channel flow involving air-water mixtures was predicted theoretically as a function of the air concentration. The predicted relationship was checked by measurements in model channels.


Various heat-transfer mechanisms which have been previously proposed are analyzed in the light of recent experiments. Evidence is presented in favor of a vapor-liquid exchange mechanism. This mechanism is shown to explain the insensitivity of boiling heat flux to the level of subcooling. A "Reynolds' analogy" for nucleate boiling is presented in some detail. (Chem. Abst. 53, 7687a, 1959.)


Experimental data are presented for heat transfer to water in rectangular channels. For boiling conditions, reasonable correlation is obtained with the results of McAdams (AEC report ANL-5688). Burnout and density data are also presented.
An exploratory study has been made of literature pertaining to the phenomena of interfacial particles in gas-liquid systems to learn what factors influence the behavior of bubbles or other types of entrainment in both static and dynamic two-phase systems. The aim is ultimately to apply these findings and their corollaries to problems associated with filling and draining Na systems, where gas entrainment appears undesirable, both from heat transfer and hydraulic consideration. (Nucl. Sci. Abst. 10, 10,817, 1956.)

The results of this work indicate that sharp fronts can be calculated from a numerical solution of the Lagrangian equation, and that capillarity does eliminate triple-values in the mathematical solution. Capillarity and gravity are important in modifying saturation profiles when the displacement rates are not too large.

Heat transfer rates to steam-water mixtures were studied on a function of steam quality. The test set-up was a 1/4-inch tube, in which quality was varied from 2% to 85% steam by weight. Heat transfer coefficients reached a maximum at about 80% steam, then dropped sharply. Results were correlated as follows:

$$\text{Nu} = C \times (\text{Re}_s)^{0.8}$$

where Nu and Re_s are evaluated for dry steam at the operating conditions. The value of C varies with quality as follows:

- when quality = 70-80%
  $$C = 0.904$$
- 55-65%
  $$C = 0.887$$
- 40-50%
  $$C = 0.804$$

Isothermal mass transfer is studied in the case when liquid water is forced to rise by water vapor and experimental results are presented for the HDO-H_2O system. In the case of non-isothermal heat and mass transfer, results are applied to the possible recovery of heat in separating units, based on the chemical exchange between hydrogen and water. (Nucl. Sci. Abst. 11, 1335, 1957.)
When a steam-water mixture flows through a pipe, the liquid flows slower than the vapor since the denser liquid is less accelerated by the pressure gradient. This type of flow is termed slip flow. A general solution for the mathematical relations for slip flow appears difficult to accomplish and an improvement of extension of the empirical pressure drop analysis, developed by Martinelli, is proposed. When the flow in a passage no longer increases with a decrease of back pressure, critical flow exists. This effect can be attributed to the inability of any wave of pressure decrease to propagate upstream when flow velocity equals acoustic velocity. At the very high rates of expansion of critical flow, thermodynamic equilibrium is not maintained in steam-water mixtures. The resulting metastable expansion greatly increases the rate of flow over the equilibrium flow. Various degrees of metastability may occur and it does not appear always possible to reliably predict the extent of metastability. (Nucl. Sci. Abst. 11, 1106, 1957.)

A correlation is developed for estimating pressure drop in the uphill sections of pipelines. This is the "only known correlation" for this purpose which is supported by a large amount of experimental data.

Two-phase Freon-114 flow rates and pressure drops were measured in an electrically heated natural circulation loop containing two 4-ft. and two 8-ft. lengths of vertical brass pipes. The flow rates through the 8-ft. pipe first increased with an increase in heat flux, reached a maximum at 3,200 Btu/hr. ft.² and then decreased as the heat flux was increased. The maximum obtainable heat flux, for both long and short pipes, was limited to 14,000 Btu/hr. ft.² because of the limitations on the electrical heaters. The flow rate through the 4-ft. pipes continued to increase with increases in heat flux up to the maximum. An equation which assumed fog flow, or no slip, was developed from a mechanical energy balance to calculate two-phase pressure drops. This equation containing only the independent variables of heat input, flow rate, and pipe length was programmed for an analogue computer and a series of pressure drop curves, representing different flow rates, as a function of heat input was drawn for each pipe length. The calculated pressure drops were approximately 25% lower than the measured values, due primarily to the effect of slip and subcooling at the inlet end of each tube.
Various heat-transfer mechanisms which have been previously proposed are analyzed in the light of recent experiments. Evidence is presented in favor of a vapor-liquid exchange mechanism and against the widely accepted "micro-convection" mechanism. The vapor-liquid exchange mechanism is shown to explain the insensitivity of boiling heat flux to the level of subcooling. A "Reynolds analogy" for nucleate boiling is presented in some detail.


A method for the solution of problems of diffusion in a moving medium with given motion of the boundaries, is presented and used to analyze heat transfer between liquid and vapor phase at the phase boundary.


An air-lift pump arrangement provides automatic liquid transfer between columns of lengths up to 40 feet. Light- and heavy-phase flow rates are governed by independent flow controls. Design of the heavy-phase-level controller, which is a diaphragm-operated valve, is described. (Chem. Abst. 53, 9744a, 1959.)


Good mass transfer between gases and liquids occurs in an apparatus with pipes, which have noncircular sections, and at Reynolds numbers above the critical value, caused by the Prandtl-Nikuradse phenomena. The pipe sections are formed like triangles, polygons, or quadrangles (trapezoid, square, rectangle). (Chem. Abst. 52, 17,831e, 1958.)


Pressure drop and heat transfer for an air-water mixture flowing in a horizontal 0.737-in. pipe were investigated at water rates of 2 to 26 gpm and air rates of 2 to 45 scfm, where the flow of both phases was always turbulent. When compensated for kinetic energy changes Martinelli's correlation for isothermal pressure drops is applicable to nonisothermal flow.


Pressure losses and flow patterns involved in co-current vertical upward flow of gas and liquid, applications of two-phase flow in mixed vapor liquid
feed to chemical process equipment, air lift pumps, and in simultaneous pipe line transportation of oil and natural gas, apparatus required for study of problem, evaluation of errors slippage measurements, and the relationship between pressure drop and gas flow rate are presented. (Engineering Index 377 (2), 1955.)


Applications of two-phase flow in mixed vapor liquid feed to chemical process equipment, air lift pumps, and in simultaneous pipe line transportation of oil and natural gas are given. Data are presented on performance of kerosene-air and water-air systems in two-phase vertical upward flow using two test sections of different size but having same ratio of diameter to height. (Engineering Index, 388 (2), 1956.)


The liquid coefficient, $k_{1\alpha}$ was determined for the desorption of CO$_2$ from aqueous solutions with air in a bubbling apparatus in which the liquor rate, $L$, and the effective liquor height, $h$, were controlling. (Chem. Abst. 52, 19,2741, 1958.)


The coefficient of mass transfer in the gas phase was determined by absorption of NH$_3$ and SO$_2$ by H$_2$O from air mixtures at 20° in gas lifts. Empirically the gas film coefficient $k = \frac{V^{0.37}}{h} = 39.9V^{0.37} (h/20)^{0.906}$.

In dimensionless form, $Nu'_g = 0.032Re_g^{0.37} Pr_g^{0.667} (h/20)^{0.906}$, where $V$ is the gas velocity and $h$ is the submergence ratio. (Chem. Abst. 53, 10,859c, 1959.)


Initial tests of the equipment for the liquid nitrogen heat transfer experiment were conducted. The investigation of heat transfer to liquid hydrogen reached the design and procurement stage, and a high-pressure cryogenic
tank was ordered fabricated. This is a final progress report for Jan. 1 - Sept. 30, 1958, of the Aerojet-General Corp., Azusa, Calif., on Contract AF 33(616)-5552.


The high heat transfer rates obtainable at subcritical pressure with a forced-convection nucleate-boiling or even film boiling process are attractive for use in cooling components of rocket motors, nuclear reactors, and other heat exchangers in space vehicles. For many applications a knowledge of the maximum nucleate heat transfer rate (boiling burnout) and of film boiling heat transfer is required. In addition the quality of the fluid at burnout may be of importance for a particular application. Many studies of boiling burnout have been made using more or less conventional fluids; however, little data are available for the cryogenic fluids. Empirical heat transfer correlations for various fluids have not met with significant success; consequently, much uncertainty exists in predicting peak nucleate, as well as film boiling, heat transfer rates for the cryogenic fluids of interest for space vehicles. The purpose of the present study, conducted at the NASA Lewis Research Center, was to determine the heat transfer rates in the nucleate and film boiling range using liquid hydrogen as the working fluid. The heat transfer rates were measured with liquid hydrogen flowing vertically upward in an electrically heated, vacuum-jacketed tube. The heat transfer rates were measured in the stable flow region for a range of flow rates from 5 to 25 pounds per hour, inlet pressure of 30 to 70 psia, liquid subcooling at the inlet from 0 to 6° F, diameter 0.555 in., and length to diameter ratios associated with the peak nucleate heat flux from 1 to 20. The resulting peak nucleate heat flux values ranged from 8 to $3.4 \times 10^4$ Btu/hr. ft.$^2$ while the highest heat fluxes in the film boiling region were about 50% greater. Thermodynamic fluid qualities at burnout ranged from 0.01 to 0.78. The data are presented in graphical form and in terms of several correlation parameters which include the flow condition, heating rate, tube geometry, and fluid properties. The empirical correlation developed herein for the peak nucleate heat flux permits a comparison of the hydrogen data with data from studies using water and limited data from a study using liquid oxygen as the working fluids. An empirical equation was also developed by use of which the tube wall temperatures downstream of the peak nucleate heat flux (i.e., in the film boiling region) can be predicted for hydrogen.


The development of equations for predicting fuel system performance is presented in Section III. Application of these equations yields a recommended procedure for calculating the pressure drop under such conditions. The properties of JP-4 fuel from Section I are employed in the calculations to illustrate the performance of a typical aircraft fuel system in steady flight and in a normal climb to altitude.

An investigation was made to determine the effect of volumetric ratio of vapor to liquid on heat-transfer when mixtures of water and steam are passed up an externally steam-heated vertical copper tube. The volumetric ratio entering the test section could be controlled as an independent variable. Means were provided to observe the two-phase flow phenomena at the entrance and exit of the tube so as to correlate observations with measured heat transfer. Four types of flow were encountered: bubble, slug, slug-annular corresponding to extremely violent agitation on the liquid-vapor mixture, and annular where vapor was carried in a core of liquid. Only the slug-annular and annular flow types persisted over the range of vaporization normally of interest in evaporation. The volumetric vapor to liquid ratio was an important variable. Heat flux and the heat transfer coefficient increased to a maximum and then decreased with increased vaporization. The maximum occurred at the point of transition from slug-annular to annular flow at all total mass flow rates. The coefficient was independent of temperature difference and total mass flow rate. Heat transfer coefficients were roughly correlated for 50 runs on the basis of total average mass flow rate of vapor through the test section alone.


Expansion losses through nozzles are examined for the case of wet steam. Losses are assigned to three causes: (1) nozzle friction, (2) impact of water drops and steam, and (3) supersaturation. The dependence of losses on the steam-to-water velocity ratio is demonstrated.


The flow of initially subcooled water through a nozzle was varied by changing the back pressure. The limit of metastability was found by plotting the actual flow and non-flashing flow versus the back pressure. Four series of tests were run at saturation pressures of 25, 35, 45, and 55 psia. Four tests were made at each saturation pressure with initial subcooling equivalent to 10, 20, 30, and 40 psi, making a total of sixteen tests. Superheated liquid was obtained in all tests, but no definite trends were indicated by the experimental data for the variation of the metastable limit either with the amount of initial subcooling, the initial saturation pressure, or both. Most of the test points fall on or near the line of 0.60% vapor when plotted on a P-S diagram.


With increasing application made of two-phase gas-liquid flow, a study of this type of flow in various standard valves was considered necessary. The following study on 1-inch pipe is a continuation of the work on 1-1/2 inch pipe presented by R. M. Sharp as a thesis at the Georgia Institute of Technology. In developing the two-phase flow, air was used as the gas.
phase and water as the liquid phase. An apparatus was used that would allow metered amounts of both phases to be passed through various standard valves. Air rates varied from about 0.003 to 0.040 pounds per second (2.50 to 15.57 scfm) with varying water rates of 2 to 30 gallons per minute. Seven different air rates were used at each water rate. The data obtained were compared with the previous data compiled by Sharp. Agreement was found to be within the accuracy predicted by the correlation of Lockhart and Martinelli. Using this correlation, it was found that pressure losses in systems containing valves could be predicted by applying a multiplying factor to the single-phase equivalent lengths of the valves. This multiplying factor is presented as a function of $X^2$, the ratio of the pressure drop for the flow of the liquid alone to the pressure drop for the flow of the gas alone.


This is the first of a series of papers designed to: (1) clarify the terminology and descriptions of the flow patterns encountered; (2) present data on the influence of pertinent variables on flow pattern, holdup, and pressure drop; and (3) establish a general correlation permitting liquid system in upward vertical flow. A correlation is presented of data obtained on the upward vertical flow of air-water mixtures in a smooth bore tube 1.025 in. inside diameter for nine water rates from 0.00040 to 0.0421 cu.ft./sec. and for air-water volumetric ratios under flow conditions from 0 to 348. The constant average flowing pressure was 36.0 psia; the temperature was 70° F. The correlation enables the prediction of flow pattern, pressure drop, and holdup ratio for gas and liquid rates within the range tested, but is restricted as to tube diameter and liquid-and gas-phase properties. (Chem. Abst. 52, 3e, 1958.)


Results of visual observation and measurements of holdup and pressure drop are reported over a range of air-water ratios for the vertical upward flow of air-water mixtures in five tubes with diameters ranging from 0.630 to 2.50 in. Tests were conducted under conditions of constant air density corresponding with an average pressure of 36 psia and at ten constant superficial water velocities ranging from 0.0695 to 7.35 ft./sec. Tubing diameter was found to have little effect on the transition from the bubble to the slug flow pattern. Tubing diameter has a marked effect on the transition from the slug flow to the froth flow pattern and from froth flow to the ripple flow pattern. Tubing diameter has an important effect on the superficial friction factor and on the holdup. The pressure drop data for each diameter were correlated in a friction factor-Reynolds number chart. (Chem. Abst. 53, 3 h, 1959.)


A comprehensive treatise of transfer phenomena involving gas bubbles and liquids. If three assumptions can be made, which hold reasonably well in
many cases, the problem can be simplified to presentation in a two-dimensional diagram. Basic principles, literature data, and generalized mathematical formulation are treated. (Chem. Abst. 53, 9743b, 1959.)


A treatise is presented, covering: a graphical method to determine if a set of characteristic numbers represents a complete set according to Langhaar (Dimensional Analysis and Theory of Models, 1951, 166 pp.) (Chem. Abst. 45, 6478d); quantitative presentation in the triangle and the tetrahedron; units for the movement of a gas bubble in a liquid and of a liquid drop in a gas; and presentation in spatial rectangular coordinates. (Chem. Abst. 52, 15,975d, 1958.)


This article is a continuation of an earlier one (see Lemaire and Grassmann) on the dynamics of gas bubbles in liquid. A graphical method of representation of dimensionless groups is suggested.


Methods of calculating pressure drop and capacity of oil-gas pipelines are presented in this review article.


A summary of the status of various phases of the program (temperature measurement, pressure measurement, flow measurement, current, voltage) is presented and discussed. (Nucl. Sci. Abst. 12, 1471, 1958.)


Significantly improved theories of two-phase heat transfer and prediction of departure from nucleate boiling have recently been developed which for the first time are not based on empirical relationships. These theories should be critically analyzed in relation to naval reactor work and tested with all existing data from both classified and unclassified sources. Conflicting analyses of two-phase fluid flow regimes confuse this area, and essentially no data or theories are available for two-phase flow with superimposed boiling. Theories and understanding of two-phase flow with boiling should be developed, starting from proven theories without boiling, and tested against all existing data or new data as necessary. A substantial start has been made in analysis of the case of upward annular two-phase flow in vertical channels, based upon modern knowledge of boundary layer and vapor condensation principles. (Nucl. Sci. Abst. 13, 8184, 1959.)

The results of this investigation indicate that there are two mechanisms by which heat is transferred to boiling liquids flowing inside tubes. At the onset of boiling most of the heat is transferred by nucleate boiling, but, as the weight fraction of vapor increases the transfer of heat by convection becomes predominant. An attempt to separate the effects of these two mechanisms has resulted in the following equation for the two-phase convection coefficient:

$$\frac{h_{TP}}{h_1} = 3.4 h_1 \left( \frac{1}{X_{tt}} \right)^{0.45}$$

This equation is based on values of $1/X_{tt}$ up to about 1.6.


A high-speed, high-resolution photographic study was made. The test section was a transparent channel of rectangular cross section, with an electrically heated metal strip suspended lengthwise to divide the channel into two flow passages. To facilitate photography of boiling on the metal strip near burnout conditions, the burnout limits for this section were determined experimentally. An empirical equation was fitted to the points.


Variables explored in the study were liquid flow rate, gas flow rate, and film height; data were correlated in terms of liquid and gas Reynolds number; thinner films or films having lower Reynolds number were more stable. (Engineering Index 403 (2), 1957)


A mathematical analysis is presented in which equations of state, energy balance, momentum balance, and an equation of continuity are combined into an equation which is solved by a method of isoclines. This gives a relation
between the peak temperature attained in a long-tube vertical evaporator and the vapor-head temperature. The mathematical analysis is tested and found accurately applicable to experimental data on a 20-ft.-long 1-1/4 in. diameter evaporator tube covering a range of pressures below atmospheric for pure water boiling.


Unsteady flow of a flashing mixture of water and steam under saturation pressures as high as 1250 psia was studied for valve and pipe designing. Pressure drop and mass flow rate data were analyzed to determine friction factors for pipes. Properties for constant enthalpy expansion are sufficiently accurate for calculating flow rates and pressure drops. Tables of properties of water expanded isentropically from saturated liquid at several pressures are included. (Nucl. Sci. Abst. 10, 9768, 1956.)


Experiments to obtain data on circulation rates are outlined, in which x-rays are used to measure flow-rates. (Rheology Abst. 1, No. 1, 26, 1958.)


Gas-liquid mixtures are treated as foams, and equations are developed.


Experimental flow rate data are presented for saturated liquid, saturated vapor, and two-phase liquid-vapor CO₂ through a convergent nozzle and a square-edged orifice. The data cover the range from the triple-point pressure to the critical pressure. Results are also presented for sub-critical flow.


Diagrams can be given from which the flow patterns for these mixtures can be predicted with reasonable accuracy. For the pressure drop the Lockhart-Martinelli correlation appeared to be valid for plug, slug, and froth flow at atmospheric pressure only; for wave and mist-annular flow it was inadequate under any conditions. Separate new correlations are given for these cases; those for plug, slug and froth flow include the influence of gas density. The results of holdup measurements have been correlated empirically with the slip velocity between the phases. A special holdup meter has been developed enabling accurate measurements to be made.


Gamma rays emanating from a radioactive source are beamed through and are attenuated by steam -- water mixtures contained in a simulated reactor flow channel. The emergent radiation is detected by a scintillation crystal-photomultiplier tube assembly. An expression is developed which yields the void fraction when the detector output with the channel empty, filled with water, and containing the mixture in question is known. The principal sources of errors inherent in the method are analyzed and their magnitudes computed for a specific test facility. With a uniform bubble distribution in this facility, the maximum possible error in void fraction is approximately ± 0.03. The method is also applied to three idealized preferential phase distributions simulated in Lucite. However, the large discrepancy between calculated and measured void fractions illustrates the need for more refined experimental techniques where non-uniform distribution of voids are encountered. Such techniques are being developed. (Nucl. Sci. Abst. 13, 5112, 1959.)


Values of total pressure drop are presented for the flow of vaporizing water in an internally heated annulus. The results lie within +30 to -11% of the Lockhart-Martinelli curve at higher qualities and within ± 45% at lower (and more uncertain) qualities. It was found that the ratio of the two-phase pressure drop to the drop with no vaporization, both in a 0.3-in. orifice, was approximately a linear function of the quality in the vena contracta, but was only one tenth to one third as great as would be predicted if the mixture expanded as a homogeneous fluid. Prediction of orifice pressure drops is improved if slip between vapor and liquid is considered.


The flow of water and sugar solutions in a trough was investigated with the purpose of studying film thicknesses. Measurements were performed with a micrometer. This is the earliest recorded study of film thicknesses.

This article includes a general discussion of flow types encountered in transfer lines associated with flash vaporization processes. There is also a brief literature review on the prediction of drop sizes formed in lines.


Hold-up and pressure drops in two-phase flow were measured, and the results are compared with those in the literature. The air-water system was investigated in a 3/4-in. pipe which was installed vertically or horizontally. (Chem. Abst. 57, 4831a, 1959.)


Drop-size distribution and drop-velocity data were obtained for isooctane sprays in turbulent air streams using a droplet camera developed at the NACA Lewis Laboratory. Experimental spray vaporization rates, based on the mean diameter, correlated single-droplet vaporization rates. An empirical expression was derived for isooctane droplet drag coefficients. (NACA Research Abst. No. 72, Oct. 27, 1954.)


The procedure for evaluating the energy balance for expansion at nozzles, where heat transfer is present, is outlined.


A survey of the literature on two-phase flow has been made with the purpose of critically examining design methods for evaluating pressure drops in steam-water mixture flow. Several simplified physical models have been used in developing equations and correlations for predicting pressure drops and flow rates. A discussion of the factors involved is presented along with several new comparisons between estimated pressure drops and experimental data. A total of 92 references is listed. (Nucl. Sci. Abst. 2, 6243, 1955.)


Frictional pressure drops for steam-water mixtures have been determined for the following ranges of conditions: pressure 25 to 1415 psia; total
flow rate 454 to 4350 lb./hr.; quality from about 0.03 to 0.98. The steam-water mixtures were synthesized by mixing steam and water and pressure drops were measured for adiabatic flow in horizontal pipes 0.484 and 1.062 in. diameter. Considerable care was taken to insure that the method of mixing did not influence the pressure drop results and that the pressure measurements were made sufficiently far from both entrance and exit. The data are compared to standard correlations and a new restricted correlation is suggested which takes into account the pressure and flow rate dependencies. (Nucl. Sci. Abst. 12, 1472, 1958.)


Void fractions and pressure drops for steam-water flows were measured in an 0.872 in. inside diameter vertical tube at atmospheric pressure over a quality range of 0 to 4%. The test section was the hot leg of a natural-circulation loop, and the inlet flow rate ranged from 1 to 3 ft./sec. A new technique for measuring void fractions was used, and the method utilizes the difference between the gamma-ray absorption coefficients of water and steam. (Nucl. Sci. Abst. 11, 626, 1957.)


A trace of radioactive material dissolved in a liquid enables the thickness of a moving film to be determined. It was found that surface tension is not a factor in either wave formation or wave flow. A theory of flow in the viscous region with waves present is suggested. (Chem. Abst. 49, 10,6731, 1955.)


This review article discusses the problems of two-phase flow as they relate to cryogenic engineering. The author briefly reviews the design procedures which are available.


Equations are derived and discussed for the system and its design and for the losses occurring in the single-phase transportation of liquefied gases through piping systems. The losses include the losses at the pump and flashing, cool-down and trapped-liquid losses. Empirical information on the properties of insulation materials and the drag of the pipe wall on the liquid and graphs of flow and loss characteristics are given for the pumping liquid He, H, N, and O. Numerical solutions for H and O indicate that the systems can be designed for some applications so that the losses are acceptable. (Chem. Abst. 53, 9738b, 1959.)

This report deals with the development of cryogenic pumps, particularly liquid hydrogen pumps. There is an extensive treatment of the subject of orifice measurement errors arising due to presence of vapor in the liquid stream, and the effect of these errors on performance curves. The authors determined that a vapor concentration between 0.36% and 1.1% by volume led to large errors in performance curves where the pumped fluid was subjected to relatively small suction heads.


Experimental results are reported for pressure drop, during forced circulation boiling of distilled water in an electrically heated horizontal tube. Empirical correlations are presented for the variation of the static pressure gradient with weight friction evaporated and with absolute system pressure, together with correlations for the total static pressure drop from the inception of boiling to the end of the heated length as a function of the total fraction evaporated and of the absolute pressure. *(Chem. Abst. 51, 7068b, 1957.)*


This is a discussion article, summarizing the work to date. No experimental data are reported.


Means of preventing burnout during heat transfer to boiling water are discussed. The use of throttling devices is considered, to reduce the percentage of total pressure drop occurring across the tube, and thus reduce the sensitivity of the tube to the condition caused by low mass flow rate.


A review covering heat transfer and pressure drop. 70 references. *(Chem. Abst. 49, 12,8871, 1955.)*


Heat transfer, pressure drop, and water density data during forced convection and local boiling heat transfer have been correlated. These data were
obtained by the University of California at Los Angeles, Massachusetts Institute of Technology, and Purdue University. All data were obtained on electrically heated tubes through which water passed in forced flow. From measurements of the attenuation of X-rays as they passed through the tube and the water, the density of the water was obtained under heat transfer conditions. The pressure drop during heat transfer with forced convection was reduced to existing correlations. The pressure drop during local and net boiling could not be correlated. The effect of dissolved gas and scale on pressure drop was unpredictable in most cases. The density data obtained at high pressures using the X-ray measurements indicated that pressure has a very large effect on the density of water during local boiling.


The mechanism of boiling heat transfer is described including the effects of various liquid conditions. Forced convection and nucleate boiling heat transfer are considered in addition to partial film boiling. Equations are presented for various pressure ranges, flow rates, and heating element geometries from which boiling locations can be predicted. Also included is a listing of equations which define conditions under which burnout would occur. Some of the more important variables and their effect on nucleate boiling and burnout are discussed, and a glossary of boiling heat transfer terms is included. (Nucl. Sci. Abstr. 13, 2408, 1959.)


Circulation rates and over-all temperature driving forces were measured by use of a steam-heated vertical thermosyphon reboiler of standard design. The tube bundle contained ninety-six 1-in. 12-BWG carbon steel tubes 8 ft. long. The inlet and outlet nozzles measured 6 and 10 in. inside diameter. The reboiler was operated at heat fluxes up to 16,000 Pcu/hr., ft.² Temperature profiles through the central tube of the bundle were observed by means of a thermocouple probe. The profiles indicated that vaporization did not occur until the liquid had passed through approximately one quarter of the tube length. Circulation rates could be predicted fairly successfully by a modification of Kern's method including the existence of a liquid zone and use of the two-phase pressure-drop correlation of Martinelli and Lockhart for the vaporization zone. A method is proposed for estimating the over-all temperature driving force (and hence over-all heat transfer coefficients) corresponding to any heat flux value. The method predicts the existence of the liquid zone and utilizes existing correlations for convection heat transfer to estimate the coefficients for the vaporization zone. The observed behavior of water and hydrocarbon support the proposed theory. The proposed methods for calculating circulation rates and temperature driving forces correlated much of the recent laboratory data of Piret and Isbin satisfactorily.

The heat transfer and static-pressure drop for two-phase, two-component flow of oil and air were measured for flow in a steam-heated horizontal 15-ft. length of 3/4-in. extra-heavy copper pipe. Tentative correlations are presented and used in comparison of the oil-air and water-air results for heat transfer and nonisothermal pressure drop in the same test system. (Chem. Abst. 50, 13806b, 1956.)


Generalized equations of mass transfer in two-phase flow systems were obtained, taking into account the hydrodynamic interaction of phases. The concept of the dynamic surface fluctuation coefficient describing similarity of two-phase systems is introduced, which is based on fully developed free turbulence (emulsification) conditions. Analysis of available experimental data indicates that the calculation method proposed may be used in the design of diffusion equipment. (Nucl. Sci. Abst. 13, 4991, 1959.)


It is established in this article that a necessary condition for the modeling of complex processes in two-phase flow is the existence of a free developed turbulence or of an emulsification regime. The developed free turbulence regime makes it possible to pass from hydrodynamic to mass transfer phenomena and to carry out simultaneous analysis and calculations of the two.


An apparatus was constructed for the registration of the presence of water in steam, based on the determination of ohmic resistance of platinum wire, which is different when wet by steam and by water, because of the large difference in the heat transfer from the wire through steam or through water at the same temperature. (Chem. Abst. 49, 12,042f, 1955.)

This is an investigation of air-water mixture in inclined and vertical pipes. The influences of roughness and inclination angle upon the coefficient of friction are studied. (Engineering Index, No. 13,083, 1959.)


Studies of a simple jet pump with two-phase flow of air, steam, and water, with simultaneous heat and mass transfer are present and discussed. It is shown that this type flow is analogous to simpler compressible flow and that normal shocks should occur in this type of flow. A simplified model for two-phase, two-component flow is presented based on local thermodynamic equilibrium.


Performance tests have shown that small quantities of radioactive feed solutions may be pumped successfully with an air lift and that the pumping rate can easily be kept within 5% of any preset value. Air lifts were tested with columns ranging from 0.18 to 1 in. inside diameter, with water, NaCl solution of specific gravity 1.12 and UO$_2$(NO$_3$)$_2$ solution of specific gravity 1.15. Variables studied were diameter, height, and submergence of the columns; density, viscosity, and surface tension of the pumped liquid, back pressure on the system; presence of suspended solids in the system; and the humidity of the operating air. Derivations of simple equations are given and the results are presented in tabular and graphic form. (Nucl. Sci. Abst. 10, 1059, 1956.)


A capacitance method has been devised and tested which will measure the vapor liquid ratio of liquid hydrogen flowing through a transfer line. This consists of placing a capacitance probe in the transfer line. As the vapor-liquid ratio changes, a proportional change occurs in the dielectric constant of the media between the inner rod and the outer case. The change may be noted by a capacitance bridge or a null balancing oscillator circuit. The capacitance of the probe is dependent upon the volumetric quality of the fluid. If the temperature and pressure are known, the mass flow rate of the gas or the liquid may be calculated. Instability present in the indicating instrument generated a 5 to 10% error in the volumetric quality. In terms of mass flow rate, the percentage error is one-tenth to two-tenths. The correlation of two-phase flow pressure drops requires an extremely accurate determination of liquid quality. The accuracy of the present metering device will not fill this requirement.


An experimental investigation of internal-liquid-film cooling was conducted in 2- and 4-inch diameter smooth-surface tubes with hot air flows at 800° to 2000° F and Reynolds numbers from 220,000 to 1,100,000. The coolant was water at flows of 0.8 to 12% of air flow. Greater cooling effectiveness was obtained than in a previous investigation with a rough-surface tube. When coolant flows were large enough, film disturbances occurred which reduced cooling effectiveness in the same manner in both 2- and 4-inch tubes. All data were generalized by means of heat transfer correlation and data obtained over a range of coolant flows in a form which facilitates the estimation of the flow of film coolant required to cool a length of tube when the temperature and flow of hot gases are known. (NACA Research Abst. No. 23, May 20, 1953.)


Visual observations and flow analyses were made of annular liquid flow with cocurrent air flow in horizontal tubes. Experiments were conducted with air temperatures of 80°, 475°, and 800° F, air-stream Reynolds numbers from 410,000 to 2,900,000, and liquid flows from 0.3 to 21 per cent of air flows. Annular liquid films were approximately 0.0005 to 0.005 inch thick. Film surface changed from relatively smooth with the liquid annulus in the region where viscous forces are appreciable to disturbed where turbulent forces are predominant. Change in cooling effectiveness of liquid films in film-cooling experiments was related to film-surface change; surface condition could be predicted approximately knowing liquid flow and viscosity. (NACA Research Abst. No. 18, Feb. 27, 1952.)


An experimental investigation of internal-liquid-film cooling was conducted in 2- and 4-inch diameter straight metal tubes with air flows at 600° to 2000° F and Reynolds numbers from 2.2 to 14 x 10^5. The coolant was water at flows of 0.8 to 12 per cent of air flow. Visual observations of liquid-film flows were made in transparent tubes with air flows at 80° and 800° F and diameter Reynolds numbers from 4.1 to 29 x 10^3. Flows of water, water-detergent solutions, and aqueous ethylene glycol solutions were investigated. Liquid-coolant films were established and maintained around and along the tube wall in concurrent flow with the hot air. The tube wall was kept below the boiling temperature of the coolant over the surfaces covered by liquid coolant. Coolant films were relatively smooth unless the coolant flow was sufficiently high so that the liquid film was thick enough to enter the region where turbulent forces predominate over viscous forces; wavelike disturbances then developed on the liquid film.
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These disturbances resulted in increased loss of coolant from the film and reduced effectiveness of the coolant. (NACA Research Abst. No. 44, June 12, 1953.)


An investigation of film cooling was conducted in a 4-inch diameter duct at gas temperatures from 600° to 2000° F and Reynolds numbers from 400,000 to 1,400,000. The coolants were water and ethylene glycol at flows of 1 to 6% of the gas flow. During vaporization of the liquid film, coolants kept the duct wall below the boiling temperature of the liquid; little additional duct cooling was obtained from coolant vapor alone. Data were generalized over part of the coolant-flow range by use of heat-transfer relations in a form that facilitates prediction of coolant flow required to film-cool a duct for a desired length when temperature and flow of the hot gas are known.


These authors observed bubble, plug and spray flow, but no annular flow.


Theoretical considerations governing the flow of hot water through nozzles are applied to steam traps.


This discussion presents a graphical solution for determining frictional losses in pipes of various sizes carrying air and steam, together with the mathematical analysis from which it is evolved. Similar investigations carried out for other fluids may yield comparable graphical solutions, the utilization of which would aid materially in increasing the usefulness of fluid-flow data.


Thin liquid wall films flowing under the influence of high-velocity turbulent gas streams were studied for the purpose of obtaining an understanding of the mechanics of film cooling. Conditions which insure liquid-film attachment to solid surfaces without loss of an evaporated liquid to the gas stream when simple radial-hole injectors are used were found; the maximum allowable coolant-flow rate for a stable coolant film was determined (a stable coolant film is obtained when no unevaporated coolant is entrained by the gas stream as the result of interfacial disturbances); and a method for calculating the evaporation rate and the surface temperature for a stable inert coolant film was found.

In this article formulas are developed for the calculation of the pressure drop in the tubes of steam boilers with forced circulation. This development is based on the assumption of mist flow. Also some consideration is given to the stability of the flow in parallel tubes.


Formulas are developed for the calculation of the capacity of pipe lines and orifices and for the calculation of the critical pressure in condensate return systems handling saturated water.


The author discusses several applications of the derived free boundary equations, including (1) motion of a plane liquid-vapor interface, and (2) motion of a plane liquid-vapor interface in a confined medium.


Equations were derived for the determination of the film thickness and pressure drop produced by gas running in the reverse direction, based on an evaluation of the energy used in the formation of liquid profiles by the flowing liquid. The equations permit calculating the thickness of the film, the pressure loss of the gas, and the liquid consumption, without doing any experimental work. The results were tested over a wide range of gas and liquid velocities and found to give acceptable results with gas velocities from 7 to 14 m./sec. (Chem. Abst. 51, 1726d, 1957.)


Calculation of two-phase flow in pipes is presented. Design and experimental data are included. (Battelle Technical Review 7, 12,138, 1958.)


Study was carried out by cinematography of air-water mixtures in transparent 25-mm. diameter pipe, varying the proportions of air/water from 0 to 1.0, and the velocity of the mixture from 0.1 to 20 m./sec. under a mean pressure of 1.5 atm. Author finds six forms of motion of mixture, from small bubbles of air in water through complete emulsion to droplets of water in air, and establishes graph limiting these forms in function of the various parameters of flow. (Applied Mech. Reviews 2, 3358, 1956.)


Experimental data obtained from the investigation of the regimes of flow of a two-phase mixture in a horizontal pipe are presented. A description of the mechanism of flow in the basic regimes and their boundaries is given. The results of measurements of the transport of moisture and of the dynamic and total heads of the two-phase mixture are presented. The results of measurement of the thicknesses of the liquid films in the two-phase stream are given. (Nucl. Sci. Abst. 11, 1478, 1957.)


The hypothesis is advanced that both crises in the boiling process (i.e., the formation of the continuous steam film at the wall, and the destruction of this film when bubbles begin to form) are a purely hydrodynamic phenomenon: the destruction of the stability of a two-phase current existing close to the heating surface. Only free convection is considered in this
The author assumes (1) change in type of boiling is caused by hydrodynamic changes in the two-phase boundary layer and is characterized by a critical rate of vapor formation; (2) molecular friction can be neglected; (3) vapor velocity near the heated surface greatly exceeds liquid velocity. From these assumptions the author develops criteria for the phenomena in question, and demonstrates their quantitative application to data from other investigations.


220. V. F. Laditskii, "Trouble with Steam Boilers as a Result of the Separation of Steam/Water Mixture." Sovietskoje Kotloturbostroenie No. 1 (1945).

Experiments were conducted to study flow forms and particularly, to study the time for the passing of gas bubbles (vapor locks) of air/liquid and steam/liquid mixed through horizontal pipes at low pressures.


A model study of the pressure drop in the gas column of an upward annular gas-liquid flow system is described. The models were two rubber tubes with walls oscillating as to increase rapidly with increase of wave length wave amplitude, and wave frequency. The mathematical analysis of the system was extended. (Nucl. Sci. Abst. 8, 6982, 1954.)


The development of a radioactive tracer technique of measuring liquid volume fraction in a two-phase boiling system is described.

Two-phase pressure drop in boiler tubes is derived in terms of the Fanning equation, multiplied by a factor which is a function of the steam-water volume difference, total flow rate, and heat input to the system. The author discusses flow instability as revealed by peaking pressure drop with increasing flow rate. The point of instability is a function only of the specific flow rate \( G/Q \) (pounds per Btu), and may be predicted from the author's equations. Finally, it is suggested that this instability may be prevented by the use of throttling orifices to reduce the percentage of total pressure drop across the tube to a small value, thereby decreasing the sensitivity of the system to instability of this type.


The authors discuss the relations of the dimensionless groups Re, We, and Fr for the case of gas bubbles in liquids.


Heat-transfer coefficients are presented for water flowing vertically in thin rectangular channels (0.1 x 215 in.) 18 and 36 in. long and heated electrically along the entire periphery. Heat-transfer correlations are given for data along the narrow and wide faces of the rectangular test section. Burnout data also are reported with steam blanketing occurring first at the corner of the test section. The proposed correlating equation, valid at the narrow face of the test section, gives values considerably lower than those obtained in a circular pipe.


The only generalized correlation of frictional pressure gradient and liquid hold-up \( R_L \) for two-phase flow, developed by Martinelli et al., was based mainly on horizontal flow data. It was the purpose of this investigation to determine the applicability of the Martinelli correlation and adapt it to the ease of vertical two-phase up-flow. Because of the important effect liquid hold-up has on pressure drop for the ease of vertical up-flow, emphasis was placed on predicting \( R_L \). The Martinelli equations, algebraically complex, were simplified by introducing the parameters \( \phi \) and \( X \) defined as follows:

\[
\left( \frac{\Delta P}{\Delta L} \right)_{TPF} = \phi \ L \text{ or } G \left( \frac{\Delta P}{\Delta L} \right)_L \text{ or } G
\]
\[ X = \sqrt{\left(\frac{\Delta P}{\Delta L}\right)_L / \left(\frac{\Delta P}{\Delta L}\right)_G} \]

where \( \left(\frac{\Delta P}{\Delta L}\right)_L \) and \( \left(\frac{\Delta P}{\Delta L}\right)_G \) are the pressure gradients which would occur if the liquid and gas phases, respectively, flowed alone. Martinelli et al. concluded that both \( \phi \) and \( R_L \) were functions of \( X \) only and expressed the relations graphically. In analyzing the data of several investigators of gas-lift operation, it was found that the Martinelli correlation was not applicable to predicting \( R_L \) for vertical up-flow. By employing a correction factor involving the ratio of pipe length to diameter \( (L/d) \) and the liquid specific gravity \( (S.G.) \), it was found that \( R_L \) correlation could be made applicable to vertical up-flow by plotting \( R_L \) versus \( X (S.G.)^{\frac{1}{4}} (L/d)^{-0.7} \).

Different curves were obtained for the two flow regimes as defined by Martinelli et al. For horizontal flow it was found that \( R_L \) was a unique function of \( X \), i.e., one curve was obtained for all regimes. The maximum deviation of points, based on substantially all the data considered were \( \pm 0.08 \) (fraction of pipe filled with liquid) for the t-t regime and \( \pm 0.06 \) for the v-t regime. Data taken on test sections containing gate-valves diverged from those taken on test sections without such obstructions to flow. Although the frictional pressure drop correlation \( (\rho \text{ vs } \Delta P) \) could not be conclusively tested for the case of vertical up-flow, most of the data considered fell within the spread of previously reported results for horizontal flow.


The experiments were made in a small inclined-tube evaporator, with one heating tube of 1 in. copper pipe about \( \frac{1}{4} \) ft. long. The evaporator was so constructed that the velocity of flow of liquid in the downtake pipe could be measured. Runs were made with distilled water boiling at temperatures of 180°, 195° and 210° F. By means of suitable thermocouples, vapor and pipe temperatures were measured at temperature differences varying from 8° to 28° F, for each temperature of evaporation. From the readings of velocity of flow of water, of vapor and pipe temperatures and pounds of condensed vapor evaporated, the overall and individual heat transfer coefficients were calculated. The coefficients on the liquid side increase with temperature difference at any given temperature of evaporation. The logarithmic mean velocity of circulation of liquid plus vapor also varies with the temperature difference, so that the liquid coefficients bear a definite relation to the velocities of circulation. (Chem. Abstr. 24, 3680, 1930.)

This paper is concerned with the mixture-density transient response of volume-heated liquid systems subjected to a step increase in the heating rate. This problem is studied experimentally and analytically. Experimentally measurements have been made by means of X-ray absorption of the density behavior of several systems of atmospheric pressure and at about 135 psia. Liquid superheat and bubble population were determined. The analysis of the growth of a single bubble in a superheated liquid is extended to enable prediction of the density-time behavior of a boiling liquid containing an ensemble of bubbles. The theoretically predicted density transients compare favorably with the experimental data. The experimental and analytical results show the high-temperature sensitivity of the density transients and the importance of nucleation to the phenomenon.


A correlation was made of data for pressure drops with surface boiling of water flowing upward in a vertical annulus with a heated core. The pressure drop was due primarily to the acceleration of the liquid due to the formation of vapor. The data were correlated with an average error of about 30% by means of the excess pressure drop, which is defined as the surface-boiling pressure drop minus the non-boiling pressure drop at the same velocity and liquid bulk temperature. The excess pressure drop was correlated as a function of heat flux density, subcooling, and annulus dimensions, for all values of velocity and pressure.


The analysis presented has been developed for use in designing natural circulation boiling water nuclear reactors. Preliminary experimental information is given on density of steam water mixtures velocity ratios of steam-to-water and two-phase friction factors for boiling in a vertical channel with uniform heat input. Experimental results of a natural circulation 600 psi boiling facility are compared with analytical results using this method. (Nucl. Sci. Abst. 11, 3569, 1957.)


Local two-phase density measurements were obtained by gamma-ray attenuation methods. Data were converted to a slip ratio, \( \frac{V_g}{V_w} \). 


The effects of flow restriction and compressible volume, located ahead of the test section, on flow stability and burnout heat flux were surveyed experimentally with water flowing in tubes. The minimum restriction pressure drop required to stabilize the flow and result in maximum burnout heat
fluxes varied nearly linearly from 5 to 100 psi with an increase in velocity from 0.5 to 40 ft./sec. A compressible volume located between the restriction and the test section resulted in flow instability and lowered the burnout flux by as much as 80%. Correlations of the data are presented for low- and high-quality burnout regimes. (ASTIA Tech. Abst. Bull., U59-11, 2587, June 1, 1959.)


Some recent Soviet research on hydraulic resistance in the flow of air-water mixtures purports to show a very general functional dependence of this resistance on the Froude modulus. The author, S. I. Kosterin, specifically states that the deviation of the resistance for the two-phase flow in horizontal pipes from the flow resistance law of a homogeneous fluid is a unique function of the Froude number and the volume fraction of gas in the mixture. The effect of diameter is said to be reflected in the Froude number where the diameter is used as the characteristic length. The objective of this research was to examine the Kosterin correlation for its validity and applicability. Based on the definitions of Kosterin, the data of Lockhart and Martinelli, and Gazley, are reduced to the Kosterin form to show experimental similarity, and to attempt a direct correlation for comparison with the results in question. The correlation of Lockhart and Martinelli was examined in order to demonstrate any compatibility with Kosterin's separate method of treating the same kind of data. The results of the effort to correlate experimental data using the parameters given by Kosterin were inconclusive. Resistance parameters calculated from the data were several times greater in magnitude than any predicted by Kosterin. The correlation of Lockhart and Martinelli, although not perfect, was found lacking in dependence on the Froude number. Experimental verification of Kosterin's work was found to be necessary. Although the utility of the Froude modulus is doubtful as a significant parameter for correlating two-phase flow resistance data in general, some indication exists that it may influence the transition between stratified and slug flow and thus serve as an index of such transition.


High speed photographs showed that an increase in the water velocity decreased the number and size of the surface bubbles for a given density of heat flux. Visual observation of high speed motion pictures showed that an increase in the degree of subcooling had a similar effect. At a water temperature of 150° F below saturation, a water velocity of 4 feet per second, and a pressure of 30 psia the high speed motion pictures revealed cyclical formation and condensation of the vapor bubbles on the surface of the heater. Thus, at one instant numerous bubbles were seen on the heater, and 0.007 second later no bubbles were visible. The formation
and collapse of the bubbles were repeated at regular intervals, which were apparently not in phase with fluctuations in alternating or direct current power. The presence of dissolved gas increases the density of heat flux for a given \( \Delta T \) in the transition region. The presence of dissolved gases also made a distinct difference in the visual appearance of the surface boiling. The stream of water was cloudy, and many small gas bubbles were carried out in the water leaving the test section.


The purpose of this investigation was to study the effects of high density heat flux on pressure drop and limiting burnout point for upward flow of water in an electrically heated test section. Pressures from 250 to 3000 psig, and heat fluxes from 36,900 to 4,480,000 Btu/hr. ft.\(^2\) were investigated. In one series of runs, pressure drop upon inception of nucleate boiling increased, as did friction factor. Until nucleate boiling began, pressure drop remained constant. Pressure drop continued to increase after nucleate boiling began, but this was dependent on scale formation rather than on the boiling itself. The effect of flow rate on pressure drop at burnout was not determined lest the test section be destroyed.


An experimental investigation was made with water and air which determined (1) the effect of water inlet conditions upon annular film establishment; (2) the effect of water inlet conditions upon liquid film distributions; (3) the effect of liquid film distributions upon pressure drop; and (4) the relationship between air rate, mean film depth, and maximum surface disturbance height. Additionally microflash photographs were made of the established film to study surface disturbance structure. The test section employed was of two-inch plastic tubing, 120 inches long. The Reynolds number range covered was from 75,000 to 175,000. Water rates investigated ranged from 0.092 lb./sec. to 0.735 lb./sec. It was found that the entering film thickness affected the quantity of water required to establish a film throughout the test section. Throughout the range of thicknesses investigated (0.036 in. to 0.015 in.) it was found that a thicker entering film required less water flow for complete tube wall coverage. Liquid rate variation was up to 25%. Film depth profiles were made at stations located 2.5, 5.0, 10.0, and 23.5 diameters from the liquid injection point. The upstream station profiles were found to be sensitive to air rates, water rate, and inlet conditions. The downstream station profiles were unaffected by inlet conditions. Additionally the upper two-thirds of the film at this station was dependent only on air rate, water rate influenced film depths only in the lower part of the tube. Vertical symmetry existed in the profiles at all but the upstream station. In all cases, films were
much thicker in the lower part of the tube than the upper. Film depths measured ranged from 0.006 in. (upper) to 0.100 (lower). Pressure drop was measured over two lengths of test section. The pressure loss in the section adjacent to the water admitting device showed a sensitivity to inlet conditions. For constant water rate, a thin film at admission caused a higher pressure drop in this section. For the range of entering film thickness covered (0.036 in. to 0.015) the pressure drop variation exceeded 15%. The pressure loss in the downstream section was unaffected by inlet conditions. Disturbance height was found to be affected by mean film depth and air rate. A higher air rate would cause a substantial increase in wave height for a given film depth. Also, increased film depth with constant air rate caused an increase in disturbance height. It was ascertained that maximum disturbance height affects pressure drop severely. Photographs of the film surface disclosed that surface disturbance form was affected by air rate and water rate. The latter influenced disturbance structure by affecting pressure drop, and hence, air laminar sublayer thickness. A dimensionless correlation was determined for all depth measurements obtained in the upper two-thirds of the tube. Radial position was used as a parameter. (Dissertation Abst. 17, 831, 1957.)


Flow in a tube was established by injecting water through an annular slot in tube wall into fully developed turbulent air flow. Film profile dimensions, liquid disturbance height, two-phase pressure drop, and extent of film establishment were measured. Air Reynolds number varied from 75,000 to 125,000. Flows up to 0.7 lb./sec. were used. The effect of flow rates on liquid surface-disturbance character is discussed. (Engineering Index 430 (2), 1958.)


An analysis of film flow in a climbing film evaporator is presented. Equations are derived relating the film thickness to liquid and vapor properties. These equations are shown to predict the experimental pressure drop within ± 10%.


Pressure drops are reported for forced circulation flow of steam-water mixtures in a 25.5 ft. long, 1.43 inch inside diameter 0.1 inch thick, horizontal annulus. The inner surface of the annulus was uniformly heated over a range from 97,000 to 233,000 Btu/hr. ft.², exit pressures extended

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from 100 to 500 psig, and exit steam qualities varied from 0 to 60% by weight. Liquid water entered the annulus and boiling lengths up to 15 feet were investigated. Moreover, the Woods and the Martinelli and Nelson methods of calculating two-phase pressure drop were applied to the experimental conditions, and the deviations between the analytical and the test results are presented. (Nucl. Sci. Abst. 11, 979, 1957.)


Methods of calculating pressure drop in heater tubes with an evaporating fluid are outlined and illustrated. A direct computational method is used for pressures above atmospheric where velocity effects are minor. For vacuum conditions, a graphical method of back-calculation from known outlet conditions is illustrated which includes velocity effects.


The effect of pressure on the density of steam-water mixtures in natural circulation boiling in multiple rectangular channels was studied to 600 psia with saturated inlet conditions. The effect of pressure in flow rate was also studied. The ratio of the velocity of the steam to the velocity of the water was found to be correlated by the inlet velocity. For a fixed average steam volume fraction, no effect of pressure on flow rate could be found. Neither velocity ratio nor steam volume fraction could be correlated in terms of quality if a sufficient velocity range was studied. The assumption of constant velocity ratio over the channel length seems to be valid. (Nucl. Sci. Abst. 10, 3352, 1956.)


This paper presents an original method of computing the length of a capillary tube to be used for the adiabatic expansion of refrigerant. The rate of flow for a given tube may be found also. The solution is obtained by a graphical integration of the Fanning equation and does not depend upon empirical factors. Good correlation with test data has been found within the limited range of conditions investigated.


For estimating the output of separators of the formula \( Q = kDd\gamma \) is proposed, where \( D \) is the width of the launder or the radius of the cone or drum, \( d \) is size of largest particle treated, and \( \gamma \) is the specific weight of suspension in tons/cu. m.; \( k \) is a coefficient which is 180 for launders when the overflow fraction is large, 220 for cones, 250 for closed drums, and 120 for the Heberlein-Huntington type of apparatus. When the heavy fraction is appreciable, \( k \) is 350 for cones and 400 for closed-type apparatus. (Chem. Abst. 53, 872le, 1959.)

The estimation of the quantity of circulation in modern high-pressure boiler-furnace circuits is not essentially new, especially to the literature abroad. Methods popularized by Munzinger and others are based on an air-lift analogy and, while straightforward, are tedious of application. The method developed by the authors is essentially an inversion of the problem as previously conceived. It consists of solving a simple equation by the use of parametric circulation curves for the heat absorption corresponding to the leaving quality of the mixture. These are given for two assumed conditions of heat transfer, that of principal heat absorption at the bottom of the tube, and that of uniform heat absorption at the length of the tube up to the critical pressure. Most commercial applications are intermediate between these two assumptions. Examples are worked out in detail to show the application. Some effects of changing circuit design are illustrated. A method of obtaining the point of maximum circulation with respect to heat absorption directly is outlined.


The flow of a two-phase mixture of steam and water in a horizontal steel tube with an inside diameter of 0.484 in. was investigated. The method developed consisted of mixing steam from a high pressure, high temperature steam generator and water from a high pressure pump. The design and construction of the equipment required much time and the solution of many difficult engineering problems. The data of the author plus the data of Wickey and Mosher were correlated and the ranges covered were: (1) pressure, 25-1415 psia; (2) total flow rate, 454-4350 lb./hr.; and (3) quality, 0-10. Two pipe diameters were used -- 0.484 and 1.062 in. A correlation of the data which took into account the pressure and flow rate effects on the pressure drop was shown. Other correlations were discussed and some changes in flow pattern correlation were suggested. (Dissertation Abst. 17, 2952, 1957.)


Flow forms and separation rates of two-phase fluid systems in horizontal pipes are discussed. The importance of the problem for various industries is mentioned. Flow through tubes of 25, 50, 75, and 100 mm. diameter, and annular flow through a 50 mm. tube are analyzed. (Engineering Index 407 (2) 1957.)

Detailed visual observations and cinematographic photos were made of the flow of air/water mixtures in horizontal pipes of diameters = 25, 50, 75, and 100 mm. and in the range of gas contents, C, from 0 to 1. Velocities of the mixture ranged from 0.2 to 6 m./sec., and up to 20 m./sec. for the pipe of diameter = 50 mm. with pressures of = 1.8 to 2 atm. at the entry and = 1.3 atm. at the outlet. This investigation made it possible to construct the first accurate charts of the ranges of the flow types of gas/liquid mixtures, and to draw a number of conclusions as to their behavior. (Nucl. Sci. Abst. 9, 4133, 1955.)


In calibrating a densitometer by gamma rays, designed to measure the volume concentration of vapor in a tube for testing of a nuclear reactor to boiling it is necessary to produce an emulsion of uniform density. The problem was resolved by a method of double weighing.


This paper presents the results of experiments with the flow of saturated boiler water through from one to four knife-edge orifices arranged in series. A useful equation is developed to conform to both the available published data and the author's experimental results when the back pressure on the orifice is at or near barometric condition.


Recent French work on the dynamics of two-phase flow in which the relationship between the Reynolds, Weber, and Froude numbers is represented graphically in a tetrahedron, is appraised.


Two-phase critical flow of steam-water mixtures has been investigated over a pressure range from 4 to 43 psia and a quality range from saturated vapor to 1% (weight) vapor. Discharges were measured from 1/4, 1/2, 3/4, and 1 in. pipes and from annuli of intermediate cross-sectional areas. The experimental mass flow rates are always greater than the value calculated on the
basis of a homogenous flow model. Several empirical methods for correlating
the data were determined, and comparisons are presented of the predictions
of several analytical flow models. (Fuel Abst. 23, 1662, 1958.)


Pressure losses and evaporation rates were evaluated for the evaporation of
water into superheated steam at pressures up to 1500 psia. Some drastic
assumptions as to the flow conditions were necessary, and a hypothesis is
put forward which, if confirmed, would simplify the complicated two-phase
flow problem at high pressures and velocities.

263. A. J. Nekrasov, The Exact Theory of Waves of Set Form on the Interface of


The equations are derived for making rough calculations of the pressure
drop required to produce a given mass flow through a subassembly for a
given heat generation for cases where the vapor volume fraction is 0.9 or
less. The ratio of vapor velocity to liquid velocity is left as a para-
meter that is varied from unreasonably low to unreasonably high values.
(Nucl. Sci. Abst. 12, 10,532, 1958.)

265. R. B. Nicholson, Sodium Boiling -- Explanation of Section IV 4 of my July
2, 1957 Memorandum of "Sodium Boiling Calculations," Report No. AECU-3699,
1958.)


Film-type distillation in tubes of unit mass transfer and equivalent height-
to-diameter ratio larger than 100 may proceed under laminar, laminar-to-
turbulent transition, and turbulent vapor-phase flow conditions. Equations
are given for determining the mass transfer coefficients under the various
conditions. The use of spiral turbulence promoters-in tubes increases
the mass transfer coefficients two to three times. Stable operation can
be achieved under emulsification conditions. (Nucl. Sci. Abst. 13, 4992,
1959.)

48, 946 (1954).
The effect of slip velocity on circulation in boiler tubes is analyzed in detail and the results are as follows: (1) If data on the actual value of slip velocity are available, its effect on specific weight can be taken into account theoretically. (2) Slip velocity is conveniently defined as a dimensionless ratio, \( \sigma \), the ratio of slip velocity to equivalent water velocity in the tube. (3) The variation in specific weight, as a result of slip velocity, is found to be as great as 25% for high values of \( \sigma \). Graphs are presented showing the effect of \( \sigma \).


Nusselt developed the basic equations of film flow from force balance considerations, assuming no shear or wave motion at the gas-liquid interface. The film thickness is given by:

\[
\Gamma = \frac{2 \, g \, y_1^3}{3 \mu_L}
\]

where \( \Gamma \) is flow rate per unit of periphery and \( y_1 \) is film thickness. This reduces to the familiar equation, \( f = 24 / Re \), for viscous flow.


Each year, in this journal's annual section on Chemical Engineering Fundamentals, developments in fluid dynamics are reviewed, including some topics in two-phase flow. For other annual reviews of two-phase flow in the same journal, see M. Weintraub et al.


Experiment results are presented from an investigation of the effects of spinning flow on burnout heat flux for water flowing through 1/4 in. tubes at low pressures and temperatures. Results indicate benefits on the order of 20% improvement of heat flux for short tubes (for equal pumping power) but not as much as had been anticipated. Heat fluxes as high as 8.5 x 10^6 Btu/hr, ft^2 were achieved. (Nucl. Sci. Abst. 13, 872, 1959.)

The air-water system was chosen for study in this experimental program. Different types of turbulators, such as wire screens, orifice plates, packed sections, and spiral coils, were placed in a glass pipe test section. Various combinations of air and water rates were systematically run through the test section with one of the turbulators placed in the section. The flow patterns existing upstream and downstream of the turbulator were observed and recorded, along with the pressure drop across the test section and other pertinent information. This procedure was repeated for each one of the turbulators investigated. It was found that most of the turbulators employed caused temporary changes in the flow patterns existing in the system. The most common effect observed was the changing of a slugging flow pattern to an annular pattern. The annular flow pattern was usually maintained from one to five feet downstream of the turbulator. It was found that the turbulators which created annular flow patterns which were maintained for relatively long distances downstream also caused relatively large pressure drops across the test sections for fixed rates of air and water flow. The correlation proposed by Gossage for predicting the pressure drops across valves during two-phase flow was found to work satisfactorily in predicting the pressure drops caused by the turbulators when the equivalent lengths of the turbulators for single phase flow were known and when the values of $X^2$ were greater than about three.


An experimental two-phase flow study was conducted on a series of Lucite rectangular channels with aspect ratios of 2 to 16 using an air-water system at atmospheric pressure. The objectives of the study were: (1) to determine the effect of sudden changes of flow area on the density of two-phase fluids; (2) to investigate the effect of mass flow rate on the two-phase friction factor multiplier; and (3) to develop a sound method of measuring the density of a two-phase fluid in large conduits. The density of the air-water mixture changed during either an expansion or contraction of flow area; however, the magnitude of the change was not great and was readily predicted by a semi-theoretical equation. A sizeable effect of mass flow rate on the two-phase friction factor multiplier was found which was not accounted for in the widely used Martinelli
correlation. Traverse measurement of density also gave a continuous trace of the phase distribution. The method was tried on Lucite mockups of simulated two-phase flow patterns, and excellent agreement was obtained between the measured and calculated voids. (Nucl. Sci. Abst. 12, 8599, 1958.)


A gamma-ray attenuation technique is presented for measuring density and phase distribution in a two-phase fluid. A comparison is made between a "one-shot" and traverse method. The technique was evaluated on lucite mock-ups of simulated flow patterns encountered in two-phase flow and by a series of tests on an air-water system at atmospheric pressure.


Boiling heat transfer coefficients for an electrically heated 1-in. tube, vertical, natural-circulation evaporator were measured for water, isopropyl and n-butyl alcohols, carbon tetrachloride, and 35 and 50% potassium carbonate solutions. Recirculation rates were measured. Data are well correlated by use of either an empirical Dittus-Boelter form of equation or one based on bubble Reynolds and Nusselt numbers.


A generalized correlation is presented which is based on field data from a large number of flowing and gas-lift wells. The correlation is based on flow through 2, 2-1/2 and 3-in. nominal size tubing, with total gas-liquid ratios ranging from 30 to 5,000 cubic feet per barrel of liquid.


Results are presented of analytical and experimental studies for use in a program to produce a boiling water heat exchanger for the MX-1964 cooling system. Comparison of predicted and measured pressure drop is shown.


Approximate laminar boundary layer solutions for mass transfer across plane interface between two co-current parallel fluid streams are derived in the form
\[
\frac{k_1x}{D_1} = \left(\frac{\mu_1}{\rho_1D_1}\right)^{1/2} \left[\frac{U_1x}{\nu_1}\right]^{1/2} \left[\frac{U_2}{U_1}, \frac{\mu_2\nu_2}{\mu_1\nu_1}\right] \\
\frac{k_2x}{D_1} = \left(\frac{\mu_2}{\rho_2D_2}\right)^{1/2} \left[\frac{U_1x}{\nu_2}\right]^{1/2} \left[\frac{U_2}{U_1}, \frac{\mu_2\nu_2}{\mu_1\nu_1}\right]
\]

where \( p \) and \( q \) are not constants but are functions of \( U_2/\nu_1 \) and \( \mu_2/\rho_1 \).

It is suggested that the boundary layer theory provides a more realistic physical picture than either the Lewis and Whitman stagnant film theory or the Higbie penetration theory.


4 and 6-in. steel pipes were installed in parallel on a straight horizontal run of 76 ft. to investigate two-phase flow in large pipes. The flow sheet of system is shown. Single-phase pressure drops were experimentally determined and were compared with values calculated by use of roughness factors of 0.00015 and 0.0015. Results are compared with other experiments. (Engineering Index 408 (1), 1957.)


A review of the literature on types of boiling, heat-transfer mechanisms, bubble formation formulas for heat-transfer coefficient for surface boiling, boiling burn-out, and the autocatalytic effect. (Chem. Abst. 52, 13,693c 1959.)


Three flow patterns are considered to exist: bubble flow, plug flow, and spray-annular flow. The presence of spray in the vapor phase is explained as being due to bursting of vapor bubbles at the interface.
Local boiling pressure drop data for forced circulation of distilled water in a uniformly heated tube is correlated within ±20% over a pressure range of 45 to 100 psia. Graphical comparison of local boiling pressure drop to isothermal pressure drop shows a maximum ratio of approximately 2.6.

For certain applications the transfer of liquid hydrogen through uninsulated transfer lines may be practical and convenient even though the steady state heat flux may be high. The heat transfer coefficient from a surface to a saturated vapor condensing on the surface may be calculated by means of standard equations involving the surface-to-condensate temperature gradient, dimensions of the surface, and properties of the condensate. Applications of these equations to liquid hydrogen transfer may be attempted using liquid air as the condensate and correcting for the superheat of the surrounding air; however, the condensing surface being at a temperature below the freezing point of the condensate causes frozen air and ice crystals to be mixed with the liquid and produces a slushy condensate with unknown properties. Observations of actual condensing films reveal that the thickness and solid air content is greatly affected by air disturbances. Because of uncertainty about the nature of the condensing film and the unknown effects of liquid hydrogen flow rate and quality, experiments were made and the results reported here on the data obtained on the heat transfer coefficients for uninsulated lines in which liquid hydrogen is flowing. Measurements were taken on flow rate, quality, ambient conditions and transfer line geometry. Flow rates varied from 6 to 23 liters per minute, quality at the end of the line ranged from 0.03 to 0.35 and the heat flux for all lines was 1.1 watts per square centimeter for still ambient air and 2 watts per square centimeter when a wind of 15 miles per hour was blowing across the test section. Another problem encountered is the friction pressure drop due to flow of a two phase fluid. Correlation in this field is made with some additional work.
An experimental investigation is reported on the flow of air-water mixtures in a number of horizontal rectangular Lucite test sections assembled in various combinations to permit the study of the effect of a sudden change in flow area on the significant flow parameters. A technique is described for measuring the volume fraction of each phase. The factors influencing the volume fractions, flow patterns and slip ratios are set forth, and the energy losses associated with an abrupt expansion or contraction are described. A correlation based on the experimental results is presented.

Semirigorous equations are developed for flow of flashing liquids in pipe lines. These are applied to flow, and computed correlations are presented for the pressure drop and vapor fraction. (Battelle Technical Review 5, 3949, 1957.)

The article presents an analysis to obtain the correct nonlinear temperature distribution and heat transfer rates in a liquid condensate film flowing downward, assuming no shear stress at the liquid-vapor interface. The effect of cross flow within the film is included.

This is a survey paper, reviewing the information representative of various features of the nucleate boiling process. Both convective and pool boiling are examined.

This paper presents analyses showing the effect on rates of condensation of vapor shear stress at the liquid-vapor interface. Both laminar and turbulent films are considered and are combined to give analytical results for
the case of laminar flow on the upper portion of a plate and turbulent flow on the lower portion. Flow acceleration and momentum changes are neglected in the analysis. The physical properties are assumed to be constant.


The topics which are discussed in this review are transpiration and film cooling, heat transfer in rough tubes, nucleate boiling, heat-transfer to fluids near the critical point, and flow with internal heat generation. Reference has been made to some of the principal sources of information. Although the given bibliography is relatively extensive, it cannot be considered complete, and the interested reader may wish to use the 74 cited references as a further guide to the literature.


An experimental investigation was conducted to determine whether any relationship exists between the friction and the heat-transfer coefficients in the region of nucleate boiling with forced convection. The water was heated by passing an electric current through the tube wall. The experimentally determined values of the friction and heat-transfer coefficients were given approximately by the equation $C_f/2 = C_H$. This is the relation that one would expect on the basis of Reynolds analogy for turbulent flow either without a laminar boundary layer or with the laminar boundary layer when the Prandtl number is unity. It appears therefore that the effect of the bubbles is a hydrodynamic one, leading to an increase in heat exchange as well as in momentum exchange.


The running ahead (slip) of steam bubbles was investigated in tubes 20.3 ft. long and 2.25 to 3.25 in. inside diameter with various steam quantities and for pressures up to 570 psi. It is shown that the relative velocity rises materially with reduction in specific weight of the mixture, or with increased steam content, but drooped considerably with rising pressure. The tube diameter proved to be of small influence in the range investigated. The frictional resistances of the steam-water mixture are considerably higher than with pure water. The author suggests that this "surprising" result may be explained by the greater turbulence caused by rising bubbles.

The simultaneous flow of natural gas with kerosene, water, and SAE 40 motor oil was studied in horizontal tubes. For steady flows an empirical correlation was obtained by plotting a "fictitious" friction factor versus $\frac{G_L}{G_g}$ where the friction factor is defined as

$$f' = \frac{g \frac{D_p}{\rho_g}}{2g g} \left( \frac{\Delta P}{\Delta L} \right)_{TPF}$$


An investigation was carried out to study the effect of flow conditions on heat transfer and pressure drop accompanying the two-phase flow of steam and water up a vertical tube. The tube was heated by a steam jacket. Viewing sections at the tube inlet and exit permitted visual bubble and slug flow, slug-annular flow, agitated annular and smooth annular flow. As the inlet ratio of steam to water increased, the heat transfer coefficient and the heat flux increased to a maximum corresponding to the transition from agitated annular to smooth annular flow, remained constant upon further vaporization, and subsequently decreased when the exit stream became a single phase. The coefficients were independent of the temperature driving force. For a given mean weight per cent vapor, the pressure drop increased with increasing heat flux.


The film thickness experiments of Hopf (Ann. Physik 32, 777, 1910) were repeated and extended. Results are recorded as a graph of depth versus mean velocity of fluid flowing in an inclined trough.


The author reports marked influence of circulation rate on relative velocity of adjoining phases. He assumes that the frictional two-phase pressure drop may be evaluated as

$$\Delta P = \frac{f_{u_L} \rho_L}{2g D_p} \int_0^L \frac{\rho_L}{\rho} \, dz .$$


Stainless-steel capillary tubes, heated electrically were employed to obtain local heat-transfer coefficients, based upon bulk fluid properties, with and without a coolant-phase change. Satisfactory correlations with the theoretical and empirical equations derived by Graetz, Drew, Hottel,

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and McAdams were obtained for heating of water flowing inside the capillary tubes at constant mass flow rates. However, no correlation was observed with these equations when a coolant-phase change occurred within the tubes. For coolant phase-changing conditions, empirical correlations of local heat-transfer coefficients that included the liquid, mixed, and vapor phases of the coolant were obtained as functions of local coolant enthalpy, coolant mass velocity, and capillary diameter.

315. K. Schwarz, "Investigation of the Density Distribution, Water and Steam Velocities as well as the Pressure Loss in Vertical and Horizontal Up-Flow Boiler Tubes." Zeits. Vereines Deutsch. Ing., Forschungsheft 20B No. 445, 1 (1954). (Translated in AEC Report AEC-tr-2314.) Measurements were carried out with the purpose of obtaining reliable data for calculating the water circulation in natural circulation boilers. By using a full-size boiler model and applying novel measuring methods, the circulating water and steam rates, the distribution of density, and the velocities of water and steam flow were established for the vertical and horizontal sections of up-flow tubes during operation as well as the pressure loss for the vertical section. Hitherto when calculating the water circulation the lead velocity of steam had been based upon values established for stationary water, and the friction coefficient determined for homogeneous liquids. The new values now obtained for circulating water-steam mixtures show substantial deviations from the values known by this time, resulting in a decisive revision of the calculation of water circulation. (Nucl. Sci. Abst. 10, 765, 1956.)

316. J. L. Schweppe and A. S. Foust, "Effect of Forced Circulation Rate on Boiling-Heat Transfer in a Short Vertical Tube." Chem. Eng. Prog. Symposium Series: "Heat Transfer - Atlantic City" 49, No. 5, 77 (1953). The inversion in pressure gradient, which was found at mass velocities to be between 200 and 300 lb./sq. ft. sec., was a surprising phenomenon. This corresponds to an entering liquid velocity of approximately 3 ft./sec., beyond which there is a range in which the pressure gradient decreases with increasing velocity. At higher velocities the pressure gradient increases as would be expected. This phenomenon is explained on the basis of sonic choking at the end of the tube, which is characteristic of high-velocity flow in a straight section. The velocity of sound in the mixture of water and its equilibrium vapor is presented, and the values are startlingly low at low boiling points. The sonic choking results in a suppression of vaporization so that in this region of inversion, where there is actually a decrease in pressure gradient, there is a corresponding decrease in linear velocity even though the mass velocity is increasing. (Chem. Abst. 47, 7837d, 1953.)


The first section of the volume discusses the advances and applications of cryogenics. In the second section the liquefaction of gases is described, in particular the liquefaction of hydrogen and helium. The third section presents methods for the separation of air, helium from natural gas, deuterium from natural hydrogen by distillation, and purification of the gases.
In the fourth section cooling by adiabatic demagnetization is discussed. The fifth section presents various types of thermometers used in low-temperature thermometry. In this section various types of insulation, e.g., vacuum, gas-filled powders, fibrous materials, and solid forms, are discussed. Section seven presents containers for storing and transporting liquefied gases. The transfer of liquefied gases through lines is discussed in section eight. The last two sections report the properties of cryogenic fluids and low-temperature properties of structural materials.


Analog calculations of the Prandtl-Karman type are applied to the film condensation of a pure substance on a vertical wall under such conditions that the flow in the condensate layer is turbulent. The results agree with Colburn's predictions made by the use of his analogy, which predictions are in general agreement with the meager experimental data available. The present results are extended to condensates of low Prandtl number, such as molten metals, and, as has been demonstrated already for the case of flow in closed channels, the contribution of turbulence in this case is found to be small until high Reynolds numbers are attained. Results for the mean heat-transfer coefficient are presented for Prandtl numbers from 0 to 5 and for Reynolds numbers as high as 100,000.


In the present study air was used as the gas phase and water as the liquid phase. An apparatus was constructed which would allow metered amounts of air and water to be passed through various standard valves and fittings. Air rates varied from about 0.01 to 0.10 pounds per second (7.43 to 74.3 scfm). Water rates varied from 2 to 50 gpm. In the tests five different air rates were used at each constant water rate. From the data obtained a series of curves were constructed for each valve showing air rate versus no-length pressure drop with the parameter of constant water rate. As a result of this study it was found that the correlation of Lockhart and Martinelli could be used to predict pressure losses in systems containing valves if a multiplying factor is applied to the single-phase equivalent lengths of the valves. This multiplying factor was found to depend on the ratio of the liquid mass flow rate to that of the gas. The data for the tee and elbows studied showed the same trend in regard to a single-phase equivalent length multiplying factor as did the valves, but difficulties in obtaining sensitive pressure loss measurements precluded the formation of a general correlation that would include both the valves and fittings.

A literature survey indicates that the flow to be expected when passing a metastable liquid through a nozzle is identical with that obtained for the passage of incompressible fluid through the nozzle for the imposed pressure drop. The assumption is made that the density of the incompressible fluid is identical with that corresponding to the upstream conditions for the metastable flow. Water in a metastable condition flowing through a nozzle was studied employing, first, a nozzle used by C. W. Gorton at the Georgia Institute of Technology and, second, a two-dimensional nozzle with glass sides to permit flow visualization. A shadowgraph apparatus and its accompanying point light source were constructed. The light was directed normal to the direction of flow, and the density variations in the flow field were observed on a ground glass screen. The flow of initially subcooled water was varied by changing the back pressure, holding the upstream pressure and the temperature fixed. For purposes of comparison the variation between the nonflashing and actual flows was indicated as a function of the pressure differential across the nozzle. The experimentally observed metastable flow rates, when using the first nozzle, did not conform with the corresponding calibrated nonflashing flow for a nozzle flowing full of liquid water. The same effect was observed later in the second nozzle; this lack of agreement is explained as due to the formation of steam in the core of the flow. This steam formation was observed using the shadowgraph technique. The results of this experiment did not substantiate assumptions made by J. F. Bailey in his analytical work.


Tests conducted at Bettis Plant have yielded steady state boiling and non-boiling pressure drop data for water flowing vertically upward in rectangular channels at 2000 and 1100 psi. Available void data obtained at conditions corresponding to some of the pressure drop tests have been reviewed, and a technique for incorporating these data in an analysis of pressure drop data has been developed. Preliminary results show that local boiling pressure drop can be treated on exactly the same basis as bulk boiling pressure drop if the necessary void information is available. A procedure has been developed for estimating boiling and non-boiling pressures drops in rectangular channels at 2000 psia independently of the experimental void data. (Nucl. Sci. Abst. 12, 1472, 1958.)

A review with 54 references. (Chem. Abst. 53, 11904d, 1959.)


An analysis of two-phase homogeneous flow for air-water mixtures is presented. The equation of motion for this case is integrated. The experimental data indicated that the Blasius friction factor is applicable over a volumetric water concentration range of 0.2 to 1.0, with the viscosity of water used for evaluation of the Reynolds number.


A thermodynamic evaluation is made of the work available for, and the resistance to circulation by, natural convection in a water-tube boiler. This leads to a theory of circulation which is independent of the usual type of hydraulic theory expressed in terms of density difference. It is shown that the present theory lends itself to a more general formulation, and the treatment is developed to elucidate the general physics of natural convection in water-tube boilers. The fundamental variables are characteristic non-dimensional groups. The system is shown to possess critical limits of stability and of circulating quantity. Expressions for these are derived, and the general type of performance is given in charts.


The rate at which evaporation can occur from a surface is limited by the rate of heat flow into the surface. Because of this limitation when a liquid at its boiling point commences to flow, the proportion of vapour which forms as a result of the Bernoulli fall in pressure is less than is calculated from adiabatic expansion. A theory for the actual amount of vapour which will form is given, together with an analysis of its effect upon the velocity of flow and the quantity of fluid passed by a nozzle. It is found that although the system consists of a central core of liquid and an envelope of vapour, the calculated limiting velocity of flow, which is the velocity of pressure propagation in the system, is low. There is a critical pressure analogous to that in a gas nozzle, but here both the critical pressure and the limiting velocity are functions of the diameter and length of nozzle. Experiments are described which confirm these theoretical deductions and show good quantitative agreement with calculations.


A method is proposed for calculation of expansion of saturated water through nozzles. The theory assumes a cylindrical stream of water emerging, remaining in the superheated metastable state, without formation of bubbles, with evaporation occurring at the surface. The rate of evaporation is calculated using these concepts. It appears from the experimental results that with the lower pressures and shorter nozzles the metastable state is fairly well preserved, so that the surface is approximately as assumed, the discharge being greater than calculated due to the surface resistance to evaporation.
Physical properties of gas-liquid and vapor-liquid mixtures are suitable, in many cases, for forced convection heat transfer, all the more so because of the very high apparent heat capacity when the liquid component has a high latent heat of vaporization. Pressure drops were determined for different gas-liquid mixtures, in different experimental conditions, keeping the gas in turbulent flow and the liquid both in viscous and in turbulent flow. The following parameters were varied: tube diameter, total pressure, liquid and gas flow rates, and liquid viscosity. Experimental data can be correlated by quite simple relationships. Heat transfer properties were studied on steam-water and gas-water mixtures. In electrically heated tubings heat transfer coefficients for steam-water mixtures were determined at various pressures, at different specific flow-rates and for different liquid-to-steam flow-rate ratios, up to burn-out conditions. (Nucl. Sci. Abst. 13, 6943, 1959.)

Tests covering a wide range of flow rates provide valuable pressure drop data for these systems of oil-air-water. (Battelle Technical Review 6, 5511, 1957.)

There are several operations in the production of petroleum in which three-phase concurrent flow of fluids takes place. In some cases this type of flow necessarily must occur, such as the lifting and transportation of gas, crude oil, or condensate and water from the reservoir to the first separator in the field. In another operation, three-phase flow is encountered when glycol is injected into a pipeline at the well-head with oil and wet gas, in order to prevent freeze-ups from gas-hydrate formation. The design of piping for vertical, horizontal, and inclined multiphase flow has been done largely by the expensive route of trial and error. Poettman, et al., have analyzed data on a number of wells flowing oil, gas, and water vertically. This laboratory study was undertaken in view of the current interest in the concurrent flow of oil and gas in field-gathering pipelines along with the injection of a third water phase such as glycol.

The boiling of water and of aqueous sugar solutions in a vertical pipe and the determination of average values of the heat transfer coefficient $\alpha$ along sections of the pipe were experimentally investigated. A steel pipe (32 mm. inside diameter, height 2 m.) was heated with steam and was connected to a closed system with natural or forced circulation. A dimensionless correlation is presented, which relates $\alpha$ to physical properties and circulation velocity. (Chem. Abst. 53, 12,764a, 1959.)

Water was pumped through annuli 1/8 in. wide, 1.08 in. inside diameter, and 14 ft. long, electrically heated at their inner surfaces. Uniform and cosine heat-flux distributions were employed, as well as concentric and 30% eccentric annuli. Circumferential average local heat-transfer coefficients agreed with the Colburn j-factor correlation for turbulent flow inside tubes and were substantially independent of eccentricity. The usual definition of film temperature correlated the results best. Efflux velocities with boiling were well above the calculated maximum values for homogeneous fluids. Inlet pressures during coolant boiling were checked by two incremental calculation methods. Homogeneous or fog flow gave inlet pressures that were somewhat too high, and Martinelli and Nelson's slip flow gave pressures too low by a larger amount. A modified plot by Lockhart and Martinelli of \( \alpha \) was obtained which gives good agreement in calculating two-phase frictional pressure drop for the runs reported. It is recommended for downward flow in concentric annuli of similar dimensions.


Pressure loss due to friction was measured for conduits ranging from 3/4 in. nominal diameters containing up to three insulated copper wires. Air flow rates used gave Reynolds numbers ranging from 5000 to 50,000. All results could be correlated in terms of equivalent diameter. (Engineering Index 407 (2), 1957.)

337. L. S. Sterman, (Title Unknown) Soviet Physics, Technical 1, 1479 (1957).

A generalized correlation of froth densities of steam-water mixtures under conditions in boiler tubes is presented. (Ind. Eng. Chem. 51, 452, 1959.)


This article treats the effect of flow rate on the heat rates corresponding to film and nucleate boiling regimes. The fluid is isopropyl spirit at 2 atm. The test section was a tube of 16 mm. inside diameter.

The data from runs with several liquids are correlated by

\[ h_{TP} = \frac{7.8 \times 10^6 \times V_G^{0.1}}{\left(\frac{C_P L}{K_L}\right)^{0.2} \sigma^2 \Delta T^{0.13}} \]

This equation exhibits discrepancies from other investigations in that (1) it is independent of flow rate and (2) the dependence on temperature difference is negative. Mean length coefficients were used instead of point coefficients. The fall in the value of \( h_{TP} \) above 50% vaporized is evident in all cases.


The two-phase flow of a liquid and its vapor in circular ducts is analyzed by writing a continuity equation for each phase, a steady-flow energy equation for each phase, and a momentum equation for each phase using the one-dimensional flow approach. Because the flow is in the mixture region, the introduction of equation of state relationships to eliminate the fluid properties in terms of a single variable complicates the equations; and the desirability of using a graphical approach is indicated. Furthermore, it is shown that with the elimination of the fluid properties from the equations there are only six equations but seven unknown basic variables of the flow: pressure, \( P \); liquid velocity, \( V_L \); vapor velocity, \( V_g \); quality, \( q \); area ratio factor, \( B \); and irreversible work term on the liquid-vapor interface, \( W \); and a thrust term acting on the liquid-vapor interface, \( F \). Thus, a complete analytical solution is not possible using only the simple one-dimensional flow approach. It is shown that the area ratio factor, \( B \), is intimately associated with the wall shear stress or wall friction. Therefore, it appears that the additional information required for a complete solution must be obtained by experiment. Experimental data are needed to provide correlations for the variation of area ratio factor, \( B \), and the vapor velocity, \( V_g \) with pressure drop. It is noted that as the wall shear stress adjusts according to the intensity of the thrust of the vapor phase acting on the liquid-vapor interface, experimental correlations of area ratio and vapor velocity data must include an equivalent length-diameter ratio, \( L/D \). For small values of \( g \) it appears that the relative roughness of the duct will be a significant factor. A criterion for critical flow is obtained by a second law of thermodynamics analysis of the two-phase flow. The criterion yields a critical outlet pressure, \( P_o \), in terms of an incipient evaporation pressure, \( P_i \). It is shown that for critical flow conditions the liquid-vapor expansion curve at the duct outlet must be tangent to an isentropic expansion curve and that the velocity of the vapor phase at the duct outlet must be equal to the sonic velocity. The criterion is valid for all fluids, all line configurations, all pressures in the mixture region, and all modes of two-phase flow. The application of the criterion is limited only by the assumptions used in deriving it. (Dissertation Abst. 17, 2963, 1957.)

Data for critical flow of saturated water in pipes is analyzed; it is shown that velocity of vapor at pipe outlet must be in the order of magnitude of the velocity of sound in vapor. A prediction curve for critical outlet pressures is given and compared with available experimental data. (Engineering Index, No. 4868, 1959.)


This paper presents the results of experimental investigations using water at an initial pressure of 100 psia and over a range of temperatures from room temperature to saturation temperature. One of the most significant facts revealed by these researches is that under certain conditions of flow the fluid assumes a metastable state which greatly influences the characteristics of the process.


The effect of the length of the experimental section upon critical heat flux in forced motion of a steam and water mixture through a pipe was investigated. Pressures were varied from 76 to 180 atmospheres, velocities from 850 to 3000 kg/m^3·sec, and relative enthalpy from -0.3 to 1. The results are discussed, including substantiation of conclusions. (Nucl. Sci. Abst. 12, 314, 1959.)


It is shown that as the steam pressures circulation velocity and reduced steam velocity increase, the slippage losses decrease.


Tests in pipes 2.2 to 2.76 inches in diameter are reported. Pressures varied from 530 to 3160 psia. Critical velocities, above which no laminations occurred, were studied as functions of heat input and pressure. The existence of non-equilibrium conditions between steam and water is observed.


The thermodynamics of gas-water mixtures flowing through a Delaval nozzle is developed.


Any explanation of the nature of multiphase fluid flow through porous media must ultimately involve a knowledge of the mechanism of such flow through the individual pores of the medium. To provide quantitative information of the latter type, a study was made of gas-liquid and liquid-liquid displacements in single uniform Pyrex capillaries with diameters as small as 4 microns. Quantitative observation of air-liquid displacements with zero contact angle indicated the interfacial velocity. Consequently, this work discounts previous claims that flow is abnormally retarded in very small capillaries. For the displacement of a very viscous oil by water in a capillary initially filled with water, flow is faster than predicted by the above model. This behavior is probably due to the existence of a thin annular film of water between the oil column and the capillary wall.


Under certain circumstances, the current in a pipe with a rough surface seems to flow more easily and rapidly than in a smooth pipe in the transition from a current condition with negative friction to one with a positive
friction. A current is observed in which the friction will equal zero, i.e., the average velocity of the liquid along the wall of the tube has no component in the direction of the current in tubes placed at an angle. Relative velocity of gas in relation to liquid appears to be greater than in vertical tubes. (Nucl. Sci. Abst. 8, 2407, 1954.)


Tubes with varying (oval) cross-section are used in order to assure good exchange between gaseous and (or) liquid substances, e.g. for distillation columns. The resulting turbulent flow gives a higher separation effect at higher distillation rates. (Chem. Abst. 53, 9745c, 1959.)


A more rigorous derivation of the equation for the height equivalent to a theoretical plate than given by Westhaver was attempted, on the assumption that all resistance to mass transfer is in the vapor phase when the separation coefficient of the mixture is > 1.1. (Chem. Abst. 53, 9736f, 1959.)


Flow patterns were observed and static pressures were measured along the tube, whence the volume fraction of air in the tube, and the relative velocity of air were calculated. (Battelle Technical Review 7, 15, 907, 1958.)


Velocity and void measurements are reported for natural-circulation flow of water through heated vertical pipes.


This paper is devoted to a discussion of the elements of boiler and furnace design dealing with the problem of obtaining adequate circulation for the higher pressures now demanded by current practice. After examining the action within a simple evaporating circuit, the author indicates the procedure in analyzing waterwall circuits and calculating the circulation in boiler tubes.


A study has been made of burnout in boiling heat transfer. This phenomenon occurs as a result of a transition in the heat transfer mechanism causing the heated surface to overheat and "burn out." A survey of the literature concerning burnout in the following categories is presented: pool boiling
burnout, local boiling burnout in forced convection (no net generation of vapor), and two-phase burnout in forced convection (i.e., with net generation of vapor). An analysis is made of the latter category and a model is proposed to predict conditions under which burnout will occur. The model is based upon a spray-annular distribution of the flow. A portion of the liquid is assumed to flow along the tube wall in an annular film. The remainder is assumed to be dispersed as droplets in the vapor core occupying the center of the tube. Burnout is assumed to occur at the point in the tube at which the annular liquid film disappears. Thus an equation is developed to predict the liquid distribution and hence burnout. The model is used to correlate data on burnout for vertical-upward flow of steam-water mixtures in round and rectangular channels. (Dissertation Abst. 17, 1970, 1957.)


The flow of liquid water droplets suspended in air-water vapor mixtures is emphasized with water air mass ratios up to 0.3 and flow velocities from 350 to 600 fps. (Battelle Technical Review 6, 14,742, 1957.)


This article is largely a commentary on the results of West et al. (Trans. Amer. Inst. Mining, Metallurgical and Petroleum Engrs., Petrol. Branch 201, 217, 1954) which were found to be in error. Also included is a further discussion on the solution of gas-oil two-phase flow problems using a digital computer.


A description is given of the design and operation of an experimental apparatus for the analysis of two-phase flows similar to those occurring in boiler tubes at low pressures. Velocity and density profiles of air-water mixtures are determined across a passage in which boiling conditions are simulated by pumping air through porous walls into a water stream. Photographs of the flow patterns are also presented as a qualitative check on the quantitative data. The results obtained were (1) velocity and concentration profiles of the two-phases for various values of the flow rates of each, and (2) a classification of the flow into several patterns or regimes with quantitative data describing each regime. The data are
suitable for comparing the physical phenomena with mathematical models and for developing a more accurate theoretical treatment of the flow of boiling fluids in heated channels. (ASTIA Tech. Abst. Bull. U59-8, 1792, April 15 1959.)


Although progress has been made recently in the fields of co-current gas-Newtonian liquid flow and turbulent flow of non-Newtonian materials, relatively little is known theoretically about these complex types of flow. For this reason, results of studies in these fields cannot be applied with certainty to the co-current flow of a gas and a non-Newtonian material, a type of flow which occurs in many industrial operations and for which no data are available. In this study, air was used as the gas phase and four concentrations of kaolin clay in water were used as the non-Newtonian materials. Two of these suspensions behaved as pseudoplastics, while the other two exhibited Bingham plastic properties. Pressure-drop measurements were made in 3/4, 1 and 1-1/2-in. horizontal pipes for each of these suspensions flowing alone and co-currently with air. Suspension flow rates were varied from 0.15 to 16 pounds per second, while air flow rates were varied from 0.0015 to 0.025 pounds per second. The majority of the tests were conducted in the turbulent flow region. The characteristics of the main centrifugal pump used to circulate the suspensions through the system were determined at each solids concentration. From the data obtained on each of the suspensions in the capillary tube viscometer and the three test sections, the flow curves of each were determined in both the laminar and turbulent flow regions. In the turbulent flow region, the usual Newtonian friction factor-Reynolds number relationship was found to be valid, confirming the work of previous investigators in this field. However, no significance could be found for the "turbulent viscosity" which results from using this relationship. The pressure-drop data obtained on the co-current flow of air and these suspensions in the turbulent-turbulent region was correlated within the range of ± 20% by the ø-X method of Lockhart and Martinelli.


Results are presented of a planned series of experiments conducted for the purpose of determining the applicability of a suggested method of calculating the performance of a JP-4 aircraft fuel system under two-phase flow conditions below the boiling altitude of the fuel. These experiments were performed at WADC during 1956 by Georgia Institute of Technology and WADC personnel. For the system studied, a pressure drop under two-phase flow...
conditions can be calculated using the suggested method to give a correspondence to the measured values within ± 25%, in the majority of cases. This pressure drop can be approximated as being 20% greater than the pressure drop calculated for the system when only liquid flows through it at the same total mass flow rate. Upon assuming equilibrium conditions, the vapor-liquid ratio is calculable to the same order of magnitude as that of the measured vapor-liquid ratio. The vapor-liquid ratio, the operating pressure and temperature levels for the fuel and the dynamic flow pattern of the fluid serve to affect the performance of the engine-driven fuel pump. Before a generalization of the conclusions of the report is made, additional performance data for various engine fuel-transfer systems should be analyzed.


The validity of the Nusselt equation for film thickness is demonstrated for Re < 1000, even when waves are present on the liquid surface. Studies were performed in vertical tubes.


Experimental procedures and techniques are described which allow the convenient determination of the point at which critical flow occurs with saturated water in a piping assembly. Values of upstream pressure temperature and the maximum discharge flow rate were investigated using these procedures. Some data are presented in examples which illustrate the techniques. The significance of the critical flow phenomenon is discussed when it occurs in the piping of a nuclear reactor. Also discussed is the effectiveness of temperature monitoring elements located in or near the region of critical flow. (*Nucl. Sci. Abst. 12, 424, 1959.*)

372. M. Weintraub, et al., "Flow of Fluids." *Ind. Eng. Chem.* 38, 6 (1946); 40, 32 (1948); 41, 44 (1949); 42, 55 (1950); 43, 90 (1951); 44, 68 (1952); 45, 74 (1953); 46, 112 (1954); 47, 558 (1955); 48, 532 (1956); 49, 497 (1957); 50, 447 (1958); 51, 367 (1959).

The fluid flow section of the annual Unit Operations Review in this journal discusses prominent developments in the field of two-phase flow. It is particularly useful for papers delivered at various society meetings. For other annual reviews of two phase flow in the same journal, see A. K. Oppenheim et al.


The flow of gas and oil through a reservoir can be described mathematically by two second-order non-linear partial differential equations which must be solved simultaneously. All derivatives were replaced by finite differences to bring the equations into a form suitable for digital calculations. A number of finite difference formulations were investigated.
and one form was found which resulted in stable convergent solutions. This form was used to obtain solutions for both radial and linear systems producing by solution gas drive.


A simple analysis is presented for predicting pressure loss and density factors for two-phase, one-component annular flow with and without heat generation. All four combinations of laminar and turbulent flow in both the annulus and core are considered. The analysis is based on assumed velocity profiles and matching velocity and shear stress at the liquid vapor interface. The theory is found to compare favorably with experimental results on both vertical and horizontal sections. The application of the theory to natural circulation steam boilers is also presented. (Nucl. Sci. Abst. 11, 1021, 1957.)


Research at University of Oklahoma provides calculation methods for solving two-phase pressure drops, and aids in making economic studies of single lines to chart presented that shows type of flow that would exist under given set of mass flow rates. (Engineering Index, 380 (2) 1955.)


This article describes the assembly and testing of a rotary concentric-tube distilling column, in which the rectifying section is an empty annular space formed by the inside surface of a stationary outer cylinder and the outside surface of a rotating, closed, inner cylinder.

Specification of the heater and cooler characteristic values determines a characteristic flow rate and temperature distribution in a natural convection loop. When the temperature is restricted to values lower than the boiling point, a steady equilibrium flow is observed, but when the temperature is not so restricted, a periodic oscillation of the flow rate and temperature may be observed even though the heat input and the cooling water properties are held constant. Attention was concentrated on these oscillatory modes of operation. The objectives of the study were to measure the characteristic properties of the various modes of operation and to define a mathematical model which was based on the fundamental principles of fluid dynamics. Then with the help of the model, the experimental observations were interpreted and some general conclusions were drawn.

The equation of motion, the continuity equation and the energy equation were written for an ideal, transient two-phase flow system. Certain functions could not be defined theoretically and these were defined empirically using steady state data. The equations would have to be solved on a high speed digital computer if a good approximation to the true behavior of the loop were desired. A simple, open-ended natural convection model was studied for instability. This analysis indicated that an unstable system has three properties. (1) The driving force must be generated in the vertical riser and not in the heater. (2) The product of the coefficient of expansion of the fluid and the height of the vertical riser must exceed a certain value which is determined by the frictional resistance of the system. (3) The period of an open-ended system is approximately equal to the time that is required for a slug of fluid to travel through the heater and the vertical riser. A similar model for the loop was studied on an analogue computer. The solution which was obtained agreed reasonably well with the experimental data and a better solution could be obtained by using a larger computer. A constant volume system, one with no surge tank, was studied briefly. It was found that the flow rate could be adjusted by adjusting the mass of the fluid in the system and that the flow rate is practically independent of the heat input to the system. Therefore, it is possible to obtain a high transfer coefficient in the heater and cooler and still have a stable system by using a constant volume two-phase system. (Dissertation Abst. 15, 2143, 1955.)

A natural-circulation loop with water as the circulating fluid was studied for a range of operation covering two-phase flow. The work reported is concerned with the periodic oscillations of the flow rate and fluid temperature. The oscillations occurred even with constant heat input and constant cooling-water properties for the heat exchanger. The analytical approach includes a theoretical analysis of an open-ended system and numerical solutions obtained with an analogue for a simplified loop system. Also presented are the equations of motion, continuity, and energy, which were developed for a transient two-phase flow model for adaptation to more detailed numerical evaluations. (Nucl. Sci. Abst. 11, 1021, 1957.)

The effects of Freon-12 mass flow rate, progressive evaporation, evaporation temperature, and oil contamination were studied. Some of the data have been treated statistically and correlation coefficients have been obtained. These data show a large variation in the heat transfer rate with temperature difference, evaporation temperature, and progressive evaporation. Little variation was found with the mass flow rate and the oil contamination.


The authors discuss the apparatus and method used in determining the point of condensation in diverging nozzles. The discussion is restricted to nozzles with very short throats and with angles of divergence greater than 2 degrees. As a primary result of the work described, the authors locate the Wilson line for continuously expanding steam at the 4.5 per cent moisture line on the Mollier diagram. Condensation points and sizes of steam droplets are discussed for various pressure and temperature conditions before expansion and for various back pressures.


The heat flux $q_c$ corresponding to the transition from nucleate boiling to film boiling in forced convection water flow is determined by the physical parameters and the water velocity. Use of force balance, material balance, and energy-balance equations and dimensionless analysis gave the following functional relation between dimensionless groups: $\left( \frac{q_c}{r} \right) \left( \frac{v}{g c W} \right)^{0.5} = f(\gamma'/\gamma, C_p \Delta t_h/r, W_l/r)$, where $r$ is the latent heat of vaporization, $v$, $c$, $\gamma$, and $C_p$ are the kinetic viscosity, surface tension, specific weight, and specific heat of the liquid respectively, $g$ is the acceleration of gravity, $W$ is the velocity of liquid flow associated with gravity, $W_l$ is the mean linear liquid velocity with respect to the heated surface, $l$ is a linear dimension of the system, $\Delta t_h$ is the number of degrees the liquid is subcooled below the saturation temperature, $t$, and the superscript $''$ refers to vapor properties. (Chem. Abst. 53, 12,761f, 1959.)


The several types of flow mechanisms possible in two-phase flow defined and their order of occurrence given at a constant liquid flow rate and increasing gas flow rates. The characteristics of two-phase flow, which
cause variable data are presented which provide a basis for design of a smoothly operating two-phase system. The favorable characteristics of orifice in a two-phase flow stream are described, and the pressure drop equation across an orifice for two-phase flow is developed. An example of the proper use of the included data is given. (Nucl. Sci. Abst. 10, 9766, 1956.)


Observations show that gas bubbles rising in water carry along a considerable quantity of water. A new equation for the evaluation of tests on water circulation is given with regard to this effect. It is possible now to compare qualitatively results by different authors and to explain anomalies arising. (Nucl. Sci. Abst. 12, 1664, 1958.)


A method for calculating the density distribution in a boiling system which takes into consideration explicitly the relative velocity of the vapor and liquid is presented. (Nucl. Sci. Abst. 10, 8673, 1956.)


A brief bibliography of Russian literature on bubble dynamics and nucleation, boiling heat transfer, burnout heat flux, and two-phase flow, is presented. The author points out that, in general, Russian researchers place great emphasis on the analytical approach, performing simple experiments to verify empirical models or analyze the influence of one or two parameters only. (Battelle Technical Review 7, 6917, 1958.)


A method for estimating the heat transfer to the film coolant is presented. It is demonstrated experimentally that increasing the film-cooled length of a cylindrical section requires more than a proportional increase in the film-constant flow rate. Experimental data are also presented for the loss in specific impulse when water is used as the film-coolant. The rocket motor experiments reported herein were conducted with a 500-lb. thrust, 500-psia combustion pressure rocket motor.