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THE EFFECT OF PRESSURE ON BOILING DENSITY
IN MULTIPLE RECTANGULAR CHANNELS

by

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THE EFFECT OF PRESSURE ON BOILING DENSITY
IN
MULTIPLE RECTANGULAR CHANNELS

by

J. F. Marchaterre

ABSTRACT

The effect of pressure on the density of steam-water mixtures in natural circulation boiling in multiple rectangular channels was studied to 600 psig with saturated inlet conditions. The effect of pressure on 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.

I. INTRODUCTION

The density of a boiling mixture is a complicated function of a great many variables. Since the calculation of water flow with natural circulation boiling in vertical channels requires a knowledge of driving head or density difference between riser and downcomer, it is desirable to have a method of determining the effect of various parameters upon boiling density. This is essential in the design of natural circulation evaporators, boilers, and boiling reactors. In the case of a boiling reactor, where the water also serves as a moderator, the neutron economy is also strongly dependent upon the density of the boiling mixture.

A schematic of a flow mechanism for boiling is shown in Figure 1. This is not necessarily correct, but it will serve to illustrate the problem. In the diagram there is represented a channel with uniform heat addition at the walls. Water enters the channel with its bulk temperature below saturation. As heat is added, its temperature rises to the point where it reaches saturation temperature. At this point boiling begins and a large number of small bubbles are created. These bubbles will expand and coalesce upon rising. If the channels are sufficiently small, the bubble diameter will rapidly become large compared to that of the channel. When this occurs, a "slugging" mechanism of flow, wherein water is lifted on a conveyor of vapor for an interval of length, should come into effect.

Figure 1 SCHEMATIC OF FLOW MECHANISM FOR BOILING

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It is also possible that a region might be reached where the percentage steam generation is great enough so that the vapor no longer acts as a conveyor, but channels itself, so that vapor and liquid flow simultaneously in separate channels having a common surface.

If it could be assumed that the steam and water velocities were identical at every point along the tube, then relationships could be easily developed to show the effect of pressure on density. However, the velocity of the steam is always different from that of the liquid due to buoyancy effects. If this effect were known as a function of the operating parameters, then the density of the boiling system could be predicted.

Before the flow in the system is known, the frictional pressure losses must be known. The pressure drop in the non-boiling region can be predicted by the Fanning Friction Equation.

The calculation of pressure drop in the net-boiling or two-phase region presents more difficulty. Although there has been appreciable work in the field of two-phase flow, no completely satisfactory design method has yet been developed. The most widely used methods are the Martinelli correlations and the friction factor methods. Although they can be used successfully in many cases, they are subject to serious criticism.

II. PURPOSE AND SCOPE

The purposes of this investigation were to measure experimentally the boiling density of a natural circulation boiling system and to analyze and correlate the experimental data with the operating variables of pressure and heat flux.

The experimental work was confined to boiling density measurements for a test section consisting of 4 multiple rectangular channels, 7/16" x 3-11/16" x 48", and to the measurement of pressure drops over a 44" section of the 4-ft heated section. The approximate ranges of variables covered in the experimental work were:

Power Density:	13 to 50 kw/liter
Pressure:	114.7 to 614.7 psia
Inlet Velocity:	1.52 to 1.83 ft/sec
Exit Quality:	1.9% to 8.2%.

The inlet water was near saturation temperature. The exit quality is a thermodynamic weight quality computed from a heat balance.

Additional data to extend the range of variables were taken from the data of Flinn and Wimunc,⁽⁶⁾ the data of Cook,⁽³⁾ and preliminary data of Flinn and Lottes.⁽⁷⁾ The data of Cook extended the 614.7 psia velocity range down to 0.6 ft/sec. The data of Flinn and Wimunc and of Flinn and Lottes extended the velocity range of the 264.7 and 614.7 psia data to 3.1 ft/sec.

III. LITERATURE SURVEY

Few data are available in the literature for the calculation of the density of steam-water mixtures during boiling.

Behringer⁽¹⁾ determined the relative velocity of steam bubbles in boiler tubes from a still column of mixture in vertical tubes. The pressure drop along the height of the column was obtained by means of a pressure-balancing testing tube, thus giving the specific gravity value of the mixture. Utilizing the value thus obtained along with the known heat input, the relative velocity was calculated. Experiments at various pressures up to 40 atmospheres were conducted and showed that the relative velocity decreased with increasing pressure and increased with decreasing specific gravity. The effect of tube diameter upon the relative velocity was evident in the range of low pressure.

Schurig⁽¹⁴⁾ presented a method for determining the flow rate of water and the relative velocity of steam. Steam pressures ranged up to 40 atmospheres. The relative velocities determined in circulating mixtures differed strongly from the results of P. Behringer in still mixtures. Also, it was shown that the resistance to flow of steam-water mixtures was different from that of homogeneous liquids.

Zmola and Bailey⁽¹⁷⁾ discussed the principal features of a nuclear reactor from which power is removed by boiling of the coolant within the active core. Calculations based upon simple theoretical models were presented in performance chart form to display the relation of influencing variables. They presented experimental results obtained from systems near atmospheric pressure in which boiling was produced by electrical resistance heating of the liquid. Densities were determined by the attenuation of gamma rays from an iridium-192 source. The data of Behringer⁽¹⁾ and preliminary data of Cook⁽³⁾ were used to extend the range to higher pressures.

Schwarz⁽¹⁵⁾ presented data for the calculation of water circulation in natural circulation boilers. Experimental data were taken at 20, 40, 60 and 80 atmospheres. Densities were determined by the attenuation of gamma rays from an iridium-192 source. Considerable deviations from the results of Behringer and Schurig were found.

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Lottes⁽⁹⁾ in a resumé of boiling studies at Argonne National Laboratory presented a hydrodynamic approach to the natural circulation problem; this differed from the approach of previous investigators in that the steam velocity relative to the water velocity was considered. The data of A. S. Jameson and E. A. Wimunc were used to show the effect of pressure on relative velocity to 250 psig.

Cook⁽²⁾ presented preliminary data at 600 psig. These data showed that the mechanism of flow at 600 psig is one which may be logically reasoned. The same mechanism of flow was observed at low pressures in glass channels, where vapor specific volumes were 25 times higher than at 600 psig.

Frictional pressure drop during two-phase flow is difficult to evaluate. H. S. Isbin⁽⁸⁾ and others have prepared a comprehensive survey of two-phase frictional pressure drop from the literature and have shown comparisons of the various calculating methods; the brief survey here is concerned only with the studies that have direct bearing on this investigation.

Dengler⁽⁵⁾ in his work on heat transfer and pressure drop found that local volumetric liquid fractions were primarily a function of weight per cent vapor, decreasing with increased vaporization. He found that it is increased by an increase in absolute pressure, is independent of total mass flow rate, and could be correlated in terms of the Martinelli parameter:

$$X_{\pi} = \left(\frac{1}{X} - 1 \right)^{0.9} \left(\frac{v_l}{v_g} \right)^{0.5} \left(\frac{\mu_l}{\mu_g} \right)^{0.1}$$

He also found that the local volumetric liquid fraction is greater in a vertical tube than in a horizontal tube with equivalent values of X_{π} . Schwarz⁽¹⁵⁾ also found this effect.

Sher⁽¹⁶⁾ measured liquid holdups and pressure drops for steam-water mixtures flowing in a vertical tube at atmospheric pressure. He found that the flow rate seemed to have no significant effect upon the relationship between volume fraction and quality.

IV. EXPERIMENTAL APPARATUS

The apparatus, shown pictorially in Figure 2 and schematically in Figure 3 consisted of a heated test section, a steam riser, a condenser, a liquid crossover to the downcomer, and the downcomer section. The flow path consisted of vertical flow through the test section to the liquid-vapor interface where the steam separates and flows through the riser to the condenser. The liquid flowed into the crossover and rejoined the condensed vapor in the downcomer. The riser was constructed of 5-in. schedule 40 pipe and the downcomer of 3-in. schedule 40 pipe. Figure 4 shows the control panel.

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Figure 2

EXPERIMENTAL APPARATUS

Figure 3 SCHEMATIC DIAGRAM OF NATURAL CIRCULATION LOOP

Figure 4
CONTROL PANEL

A. Test Section

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The test section consisted of 4 resistance-heated, 1/16", type 304 stainless steel plates, 48" long. The plates were set 7/16" apart in Teflon spacers which were held in place by a stainless steel shroud (see Figure 5). Three full channels and two half channels were employed, although this caused a minor discrepancy in flow distribution. The shroud extended for 24" beyond the plates, comprising a riser section of 0.0869 ft² cross-sectional area. The cross-sectional area of the test section was 0.0448 ft², that of the heated area was 9.833 ft², and the volume was 5.08 liters. The area between the shroud and test section was filled with stagnant water at equilibrium with the system. Heat losses in this direction were negligible. The shroud and test sections are shown pictorially in Figures 6, 7, and 8.

B. Power Supply

The test section plates were heated by alternating current from three 120-volt lighting transformers. The power input varied from 67 kw to 255 kw. Power input to the test section could be varied continuously by controlling the firing angle of a G.E. CR7503-E112 High Voltage Ignitron Contactor connected in series with the grounded primary leads of three lighting transformers.

C. Temperature Measurements

The amount of subcooling of the water was measured by two bucking iron-constantan thermopiles, one located in the steam phase above the riser and one located in the inlet to the test section. These piles were calibrated over the range used by employing a hypsometer arrangement. The arrangement of the couples in the piles is shown pictorially in Figure 9.

Temperatures in the downcomer were measured by using an averaging iron-constantan thermopile located just below the orifice.

Temperatures of the manometer cold leg, of the manometer, and, as an additional check, of the steam phase and inlet water were measured by No. 30 iron-constantan thermocouples.

The iron-constantan wires from the couples and thermopiles were led directly to a selector switch and then to a Leeds and Northrup double bridge potentiometer. An ice junction was used as a reference junction for the potentiometer.

The pile leads were also connected to a D.C. amplifier which fed into a Model AW Esterline Angus Graphic Voltmeter, 0-10 mv, enabling variations in subcooling to be watched during a run.

Figure 5

7 1/16" CHANNEL TEST SECTION

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Figure 6

TEST SECTION SHROUD

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Figure 7

CUT-AWAY VIEW OF TEST SECTION SHOWING PLATE ARRANGEMENT

Figure 8
INLET TO TEST SECTION

Figure 9

ARRANGEMENT OF COUPLES IN THERMOPILES

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D. Pressure Measurement

A pressure tap was located in the riser above the water level in the steam phase and led directly to a Heise precision bourdon tube gauge 0 - 700# graduated in 1/2# divisions.

Pressure drop measurements across a 44" section of the test section were made. The first tap was located 1" from the end of the heated section, the second was located 44" upstream. The taps led to a type W, Model 180, 15" vertical Meriam reservoir manometer. Meriam red oil with specific gravity of 2.95 was used as a manometer fluid. The pressure drop and flow manometers are shown pictorially in Figure 10.

E. Flow Measurement

The measurement of flow was accomplished by means of a 2.4", sharp-edged, calibrated orifice located in the downcomer. The orifice taps led to a Model M-182 12" Meriam inclined manometer. A 1.25-specific gravity manometer fluid was used.

F. Void Measurement

The density of the steam-water mixture was obtained by the calibration of the attenuation of gamma rays passing through the test section. The arrangement is shown schematically in Figure 11. It consisted of a thulium source (0.085 Mev gamma, 120-day half life), a Dumont photo multiplier tube and scintillation crystal, a Hewlett Packard current amplifier, and a recorder (type AW Esterline Angus Graphic Voltmeter, 0 - 10 mv). Figure 12 shows the photo multiplier tube and scintillation crystals. The coils about the arrangement were for cooling water which kept the crystal at constant temperature and protected it from the heat of the section. The beam from the source was directed between the channels of the test section producing a signal at the photo multiplier tube. Two full channels were covered and the voids at any location were the average of two channels in an approximate 1" square. The percentage voids at any point along the heated length were obtained by first traversing the heated test section, then repeating the traverse with the system full of liquid at temperature and pressure, and then with the system full of vapor at temperature and pressure. Cook and Rohde⁽⁴⁾ determined the effect on void measurements in channels of preferential void distributions and checked the validity of the assumed exponential attenuation of the gamma rays. They found that the error in measuring voids had a maximum void fraction error of -27% in the local boiling region and +8% in the net steam region.

G. Power Measurement

The power received by the test section from the transformers was measured with a Weston wattmeter Model 432. The wattmeter received its current from a current transformer (Electran type

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Figure 10
PRESSURE DROP AND FLOW
MANOMETERS

21

Figure 11

SCHEMATIC DIAGRAM OF DENSITY EQUIPMENT

Figure 12

PHOTOMULTIPLIER TUBE
SCINTILLATION CRYSTAL,
AND COOLING COILS

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H-2260), 500:1 ratio, and its voltage directly from the test section terminals. As an additional check the voltage and amperage were also measured.

V. EXPERIMENTAL PROCEDURE AND RESULTS

A. Procedure

The system was filled and the manometer circuits were bled. Power was then applied in gradual increments until a predetermined level was reached. When the pressure reached the desired level the condenser was turned on and the pressure held by controlling the flow of cooling water to the condenser. When the system had stabilized, a "run" was started and the following data collected:

1. Power to the test section
2. Operating pressure
3. Pressure drop across orifice in downcomer
4. Pressure drop across test section
5. Temperature of inlet water
6. Temperature of steam phase
7. Temperature of downcomer water
8. Temperature drop from inlet to steam phase
9. Temperature of manometer cold leg
10. Temperature of manometer
11. Point by point density measurements up the test section, taking readings only when the temperature drop from inlet to steam phase was at the same level on recorder as when the original reading was taken.
12. Barometric pressure.

When the density measurements were completed the condenser water was shut off and the condenser allowed to boil dry. The power to the test section was then shut off and the pressure held with steam from auxiliary boilers. Another point by point traverse was then made with the test section containing water at the operating temperature and pressure. With the pressure still being held with steam from the auxiliary boilers the system was drained until the density-measuring equipment indicated that the top of the test section was in the steam phase. Another set of density readings was then taken with the system containing steam at operating temperature and pressure.

B. Results

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Tables I to XXXI, Appendix I, show the converted and corrected experimental data. The total heat input and mass velocities were calculated from the wattmeter and flow manometer readings, respectively. The absolute pressure is the summation of the gauge pressure and barometric pressure. The length in boiling was calculated from a heat balance using measured heat inputs and flow rates. Uniform heat generation was assumed along the length of the heated section. Thermodynamic equilibrium at all points was also assumed.

The steam volume fraction or void fraction at a point was calculated from the relationship:

$$Y = Y_1 \left(\frac{Y_2}{Y_1} \right)^\alpha$$

This is for an assumed exponential attenuation of the gamma ray beam. This assumption was shown to be valid if sufficient absorber was present to reduce the low energy component of the source to a small value.

It was of considerable interest in these tests to determine the velocity ratio or slip, which is defined as the ratio of the velocity of the steam flowing through the section to the velocity of the water. The slip was computed from the relationship (see Appendix II):

$$\frac{C_g}{C_\ell} = \left(\frac{X}{1-X} \right) \left(\frac{1-\alpha}{\alpha} \right) \frac{v_g}{v_\ell}$$

Figure 13 shows typical curves of steam volume fraction vs length. Figure 14 shows typical curves of velocity ratio vs length.

The pressure drop data were presented as the ratio of the two-phase frictional loss to the loss if only a single phase were flowing. The single-phase pressure drops were computed using Moody friction factors for a smooth pipe. The pressure drop was measured across a 44" length starting 1" from the end of the heated section. The two-phase drop was computed by subtracting the static head and acceleration losses from the measured drop. The static head was evaluated from the experimental measurements of density. The acceleration loss was evaluated from the relationship: (12) (13)

$$\Delta P_a = \frac{G^2}{g_C} \left[\frac{(1-X)^2}{(1-\alpha)} + \left(\frac{X}{\alpha} \right)^2 \left(\frac{v_g}{v_\ell} \right) - 1 \right] V_1$$

Figure 13 TYPICAL CURVES OF STEAM VOLUME FRACTION VS LENGTH

Figure 14 TYPICAL PLOTS OF VELOCITY RATIO VS CHANNEL LENGTH

VI. DISCUSSION OF RESULTS

A. Velocity Ratio

It was of prime importance in this investigation to determine the effect of pressure on the slip and to find some means of predicting it. By a method of trial and error the values of exit slip were found to be correlated with the inlet velocity. These plots are shown in Figure 15. These give a series of well-defined curves with pressure. The data of Cook,⁽³⁾ Flinn and Wimunc,⁽⁶⁾ and Flinn and Lottes⁽⁷⁾ were used to extend the velocity range of the 614.7 and 264.7 psia data. Only natural circulation points at the exit were used to exclude the possibility that a difference in the behavior of forced and natural circulation systems due to a transient behavior of natural circulation systems would cause a difference in results. The 614.7- and 264.7-psia data are shown again in Figure 16 a, b in a logarithmic plot. These curves approximate a straight line and can be represented by the equations:

At 614.7 psia:

$$\left(\frac{C_g}{C_l}\right)_{\text{ex.}} = 2.66 V_{\text{in}}^{-0.602}$$

At 264.7 psia:

$$\left(\frac{C_g}{C_l}\right)_{\text{ex.}} = 5.07 V_{\text{in}}^{-1.08}$$

These equations will correlate the exit slip ratios to within $\pm 25\%$ over the range of data available. These equations would not be expected to be valid over an inlet velocity of 3 ft/sec.

The $\left(\frac{C_g}{C_l}\right)_{\text{ex.}}$ vs inlet velocity curves were cross plotted to give a series of curves of $\left(\frac{C_g}{C_l}\right)_{\text{ex.}}$ vs pressure at various inlet velocities (Figure 17).

Since the velocity ratio must go to one at the critical pressure the curves representing the data have been extrapolated to go through this point. Velocity ratios in this region should be considered reasonable values.

It should be remembered that the majority of these points were taken with the water entering near saturation temperature. The effect of subcooling has not been determined. Cook⁽³⁾ found that the amount of subcooling influenced the value of the slip ratio.

Although the slip data fall within the limits predicted by an error analysis, it was examined closely to see if there was any observable pattern to the scatter. A study of the data showed no observable trend.

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Figure 15a
Exit Velocity Ratio
as a Function of
 V_{in} at 614.7 psia
 $\Delta T_s \approx 0$

Figure 15b
Exit Velocity Ratio
as a Function of
Inlet Velocity at
264.7 psia
 $\Delta T_s \approx 0$

Figure 15c
Exit Velocity Ratio
vs. Inlet Velocity
at Various Pressures
 $\Delta T_s \approx 0$

29

Figure 16a
EXIT VELOCITY RATIO VS.
INLET VELOCITY AT
614.7 PSIA - $\Delta T_s \approx 0$
○ - Data of Cook
△ - Data of Flinn & Lottes

Figure 16b
EXIT VELOCITY RATIO VS.
INLET VELOCITY - $\Delta T_s \approx 0$
○ - 274.7 psia data
x - Data of Flinn & Wimunc
□ - Data of Flinn & Lottes

Figure 17 EXIT VELOCITY RATIO AS A FUNCTION OF PRESSURES AT
VARIOUS INLET VELOCITYS - $\Delta T_s \approx 0$

31

Previous investigators have attempted to correlate slip with quality and have had some success. A study of the data showed a rough correlation of this type could be developed. However, a study of the data of Cook⁽³⁾ and of Flinn and Lottes⁽⁷⁾ showed that this type of correlation broke down if a considerable range of velocities were considered.

B. Variation of Slip with Length

Figure 14 shows typical curves of velocity ratio vs length. The shape of the curve was, in general, typical. The slip started at a low value, rose rapidly to some level, and then remained relatively constant over the rest of the channel length. The initial rise extended over a longer portion of the channel length at the higher void fractions at low pressures and decreased with pressure until at 614.7 psia it was almost entirely absent and the slip started at some level and continued with only a slight increase for the rest of the channel length. The assumption of constant slip over the channel length would be a good approximation to the actual conditions in most of the tests conducted, although some deviation is shown. This assumption may not be valid in the case where the inlet water is subcooled several degrees. Cook⁽³⁾ in an investigation on the same equipment found that considerable deviation from constant slip could be expected if a large amount of subcooling was present.

C. Variation of Mean Density with Pressure

Knowing the value of $\frac{C}{C_l}$ at the exit, the steam volume fraction at the exit can be calculated from the relationship:

$$\alpha_{ex} = \frac{\frac{v_g}{v_l}}{\left(\frac{C_g}{C_l}\right)_{ex} \left(\frac{1}{X_{ex}} - 1\right) + \left(\frac{v_g}{v_l}\right)}$$

Once this value is known the variation of mean density with pressure can be computed.

Lottes⁽¹⁰⁾ derived an expression for density ratio over the length in boiling in terms of exit steam volume fraction:

$$\frac{\bar{\rho}}{\rho_l} = 1 - \frac{(\rho_l - \rho_g)}{\rho_l (1 - \phi)} \left\{ 1 - \left[\frac{1}{\alpha_{ex}(1 - \phi)} - 1 \right] \ln_e \left[1 + \frac{1}{\frac{1}{\alpha_{ex}(1 - \phi)} - 1} \right] \right\}$$

where

$$\phi = \left(\frac{C_g}{C_l}\right) \left(\frac{v_l}{v_g}\right)$$

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Values of $\left(1 - \frac{\bar{\rho}}{\rho_l}\right)$ vs exit steam volume fraction are shown in Figure 18 from pressures from one atmosphere up to the critical pressure for a slip ratio of unity. In the derivation of the above equation $\frac{C_g}{C_l}$ was assumed to be constant over the length of the channel. At pressures less than 1000 psia and for values of exit steam volume fraction less than 0.8 the effect of slip is negligible. Experimental values plotted on the curve show a deviation of less than $\pm 15\%$. Deviations are greatest at the lower pressures where the deviation from constant slip over the channel length is the greatest.

Therefore if the exit slip ratio is known, the mean density of a boiling channel can be computed.

D. Effect of Pressure on Flow Rate and Frictional Losses

For a given driving head the velocity is not affected by pressure. Figure 19 shows the inlet velocity as a function of the total driving head for channels and riser. Cook⁽³⁾ showed that exit void fractions are a close approximation to the voids in the riser, and exit void fractions were used to compute the driving head in the riser. Measured values were used for the driving head in the channels. No discernible effect of pressure can be seen.

Figure 20 shows the ratio of the two-phase frictional drop, ΔP_{TPF} , to the drop if liquid alone is flowing, ΔP_0 as a function of the mean voids over the length that the pressure drop was measured. No discernible trend within the scatter can be found, indicating that when the frictional losses are correlated on the basis of mean steam volume fraction no effect of pressure is present. Since the pressure drops measured were not incremental drops and since the steam volume fraction varied over the length in which measurements were taken, the shape of a $\frac{d P_{TPF}}{d P_0}$ curve would be expected to be somewhat different from the $\frac{\Delta P_{TPF}}{\Delta P_0}$ curve.

E. Effect of Pressure on Power Density

In the design of a nuclear reactor in which the coolant is also the moderator, the neutron economy is strongly dependent upon the density of the boiling mixture and, thus, upon the power density. The operating mean density decrease for a specific reactor is set by nuclear requirements. The range of interest is $0.1 < (1 - \bar{\rho}/\rho_l) < 0.5$.

Figure 21 shows the parameter $\left(\frac{1 - \alpha_{ex}}{\alpha_{ex}}\right)$ as a function of pressure for various constant power densities. This figure illustrates the strong dependency of the power density upon pressure.

Figure 18 MEAN DENSITY DECREASE AS A FUNCTION OF EXIT STEAM VOLUME FRACTION - $\Delta T_s \approx 0$

Figure 19 INLET VELOCITY AS A FUNCTION OF "DRIVE HEAD"

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Figure 21 EFFECT OF PRESSURE ON STEAM VOIDS-INLET
SUBCOOLING $\approx 0^\circ\text{F}$

An expression that relates the power density to pressure can be derived from heat balance and continuity concepts⁽¹¹⁾ (see Appendix III). This is

$$\frac{Q_T}{V} = \frac{h_{fg} \rho_{in} V_{in}}{L \left[1 + \left(\frac{C_g}{C_\ell} \right)_{ex} \left(\frac{v_g}{v_\ell} \right) \left(\frac{1}{\alpha_{ex}} - 1 \right) \right]} + \frac{V_{in} \rho_{in} C_p \Delta T}{L}$$

Pressure affects the ratio of velocities and the fluid properties only. For a given driving head the velocity is not affected by pressure (see Figure 19); therefore, the effect of pressure can be determined from a knowledge of the fluid properties and $\frac{C_g}{C_\ell}$ as a function of pressure.

Figure 22 shows how power density varies as a function of pressure for a constant mean density decrease. This curve is a plot of the above equation for 4-ft channel with a 2-ft/sec inlet velocity and water entering at saturation temperature. Values of $\left(\frac{C_g}{C_\ell} \right)_{ex}$ for the equation were determined from Figure 17. Values of α_{ex} at various pressures at a constant mean density decrease were determined from Figure 18. It should be remembered that this is for water entering at saturation temperature and subcooling would increase the power density greatly.

F. Void Distribution over the Channel Length

The shape of a steam volume fraction vs length curve is a function of three factors: the volumetric amount of steam being formed in the channel, the pressure, and the variation of slip with length. Of particular use in investigating the void distribution as a function of channel length are normalized void plots, i.e., $\frac{\alpha_{loc}}{\alpha_{bl}}$ vs $\frac{l'}{L_b}$. These plots have two distinct advantages: (1) the curves are pulled together and can be compared directly, and (2) the deviation from constant slip over the channel length can be studied by a comparison with an analytical solution without concern about either slip level or quality deviations. The experimental data are plotted in this way in Figures 23, 24, 25, 26, 27, and 28.

An analytical expression was written for the ratio of α_{loc}/α_{bl} as a function of the fractional distance in the boiling length, the exit steam volume fraction, the ratio of specific volumes, and the slip ratio, assuming slip is constant over the channel length and the quality varies linearly with channel length. These assumptions will be discussed in more detail later.

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Figure 22
POWER DENSITY AS A FUNCTION OF PRESSURE FOR A 4 FT CHANNEL,
INLET VELOCITY 2 FT/SEC, INLET WATER AT SATURATION TEMPERATURE
AND A CONSTANT MEAN DENSITY DECREASE

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Figure 23 $\left[\frac{\alpha_{loc}}{\bar{\alpha}_{bl}} \right]$ AS A FUNCTION OF PERCENTAGE LENGTH IN BOILING AT 114.7 PSIA

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Figure 24 $\left[\frac{a_{loc}}{\bar{a}_{bl}} \right]$ AS A FUNCTION OF PERCENTAGE LENGTH IN BOILING AT 274.7 PSIA

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Figure 25 $\left[\frac{a_{loc}}{\bar{a}_{bl}} \right]$ AS A FUNCTION OF PERCENTAGE LENGTH IN BOILING AT 314.7 PSIA

Figure 26 $\left[\frac{\alpha_{loc}}{\bar{\alpha}_{bl}} \right]$ AS A FUNCTION OF PERCENTAGE LENGTH IN BOILING AT 414.7 PSIA

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Figure 27 $\left[\frac{a_{loc}}{a_{bl}} \right]$ AS A FUNCTION OF PERCENTAGE LENGTH IN BOILING AT 514.7 PSIA

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Figure 28 $\left[\frac{a_{loc}}{a_{bl}} \right]$ AS A FUNCTION OF PERCENTAGE LENGTH IN BOILING AT 614.7 PSIA

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This expression is: (See Appendix IV for derivation)

$$\frac{\alpha_{loc}}{\alpha_{bl}} = \frac{\frac{v_g}{v_l} \left(\frac{C_g}{C_l} \right) \left[\frac{1}{\left(\frac{L}{L_b} \right) \left(\phi_2 \right)} - 1 \right] + \frac{v_g}{v_l}}{\frac{1}{\phi_1} - \frac{\left(\frac{C_g}{C_l} \right) \left(\frac{v_l}{v_g} \right)}{\phi_1 \phi_2} \ln \left[1 + \frac{\phi_1 \phi_2}{\left(\frac{C_g}{C_l} \right) \left(\frac{v_l}{v_g} \right)} \right]}$$

where

$$\phi_1 = 1 - \left(\frac{C_g}{C_l} \right) \left(\frac{v_l}{v_g} \right); \quad \phi_2 = \frac{1}{1 + \left(\frac{C_l}{C_g} \right)_{ex} \left(\frac{v_l}{v_g} \right) \left(\frac{1}{\alpha_{ex}} - 1 \right)}$$

A plot of the equation is shown in Figure 29 for a slip ratio of unity at an exit void fraction of 0.5 at 114.7 psia and 3000 psia. The curves differ only slightly, showing that the void distribution in a channel is quite insensitive to pressure for a fixed exit void fraction. The function is extremely insensitive to a change in C_g/C_l ; thus, a difference in C_g/C_l from one to three is not sufficient to enable separate curves to be drawn. This holds only for a variation in constant C_g/C_l level.

Figure 30 shows the ratio plotted at various exit steam volume fractions at 114.7 psia. The computed curve of $\alpha_{ex} = 0.745$ has the data points for a typical run plotted on it.

The deviation from the analytical solution is typical and always occurs in the same direction, decreasing with increasing pressure. Since it is greater than can be accounted for on the basis of error in void measurements, the assumptions in the derivation of the equation must be looked at more closely. These are two: the linear variation of quality with length, and the assumption that the slip is constant over the channel length. Since the linear variation of quality with channel length would seem to be a valid assumption with the water entering near saturation temperature and with high heat fluxes, and since the deviation is in the same direction as the approach of C_g/C_l to a constant value over the length, it must be concluded that the deviation is due to a deviation of C_g/C_l from a constant value over the length and that the shape of the experimentally determined C_g/C_l curves is correct.

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Figures 28e and 28f show shapes that could be attributed to a deviation from a linear variation of quality. These are at a low heat flux, as might be expected; also the actual void readings are very low and deviation is within predicted range. Again it should be remembered that these are for the inlet water near saturation temperature. Cook⁽³⁾ has found that deviation from this type of behavior could be considerable if subcooling were present.

VII. CONCLUSIONS

The exit slip ratios can be correlated to within $\pm 25\%$ over the range of data available by the inlet velocity. A study of the data indicates that neither volume fractions nor velocity ratios can be correlated as a simple function of the quality if a sufficient range of velocities is studied.

The assumption of constant slip over the channel length will not lead to serious errors in determining mean steam volume fraction, and the deviation from constant slip seems to become less with increasing pressure.

Over the range of pressure studied no discernible effect of pressure on either flow rate or friction factors could be found.

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NOMENCLATURE

A	= Area
α	= Steam volume fraction or void fraction
$\bar{\alpha}$	= Mean steam volume fraction
C	= Velocity
C_p	= Specific heat
G_c	= Mass flow rate
g	= Gravitational constant
h_{fg}	= Enthalpy
L	= Length
l	= Distance to any point in channel
l'	= Distance to any point from beginning of boiling length
ρ	= Specific weight or density
$\bar{\rho}$	= Mean density
Q	= Heat input
V_{in}	= Inlet velocity
v	= Specific volume
W	= Weight flow
X	= Quality
Y	= Void intensity reading
Y_1	= Void intensity reading when $\alpha = 0$
Y_2	= Void intensity reading when $\alpha = 1$
ΔT_s	= Saturation temperature - inlet water temperature

Subscripts

b, bl	= refers to length in boiling
ex	= refers to exit condition
g	= refers to gaseous or steam phase
l	= refers to liquid or water phase
T	= refers to total (weight flow or channel length)
44	= refers to the 44 in. length between pressure taps

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APPENDICES

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APPENDIX I
EXPERIMENTAL DATA

TABLE I

Run No.	P, psia	Q _T , kw	Q _T /V, kw/liter	W _T , #/hr	V _{in} , ft/sec	L _b , in.	$\bar{\alpha}_{bl}$	α_{ex}	X _{ex}	$\frac{C_g}{C_{\ell ex}}$	$\frac{\Delta P_{TPF}}{\Delta P_0}$	X ₄₄	α_{44}	$\bar{\alpha}_{44}$	$\frac{\Delta t_s}{\text{Corr.}}, ^\circ\text{F}$
420	614.23	168	33.10	13,640	1.71	46.87	0.319	0.510	0.0565	2.2	5.69	0.0548	0.475	0.295	0.85
423	614.18	108	21.28	12,860	1.61	45.63	0.236	0.400	0.0374	2.1	3.94	0.0337	0.384	0.202	1.21
445	614.27	204	40.19	15,080	1.89	46.91	0.344	0.530	0.0620	2.05	4.23	0.0554	0.532	0.319	0.84
452	614.39	255	50.24	14,360	1.80	47.54	0.384	0.602	0.0824	2.15	6.43	0.0736	0.586	0.361	0.50
517	614.46	134	26.40	13,420	1.61	47.28	0.271	0.505	0.461	2.1	2.57	0.0412	0.449	0.247	0.43
527	614.46	67	13.20	12,100	1.52	47.04	0.172	0.300	0.0254	2.25	2.13	0.0227	0.293	0.157	0.133
555	274.24	108	21.28	14,320	1.67	46.00	0.314	0.475	0.0302	3.2	5.98	0.0276	0.450	0.293	1.05
556	274.24	134	26.40	14,860	1.73	46.74	0.388	0.560	0.0367	2.8	9.47	0.0335	0.555	0.380	0.79
557	274.26	108	21.28	14,970	1.74	46.33	0.356	0.515	0.0291	2.6	7.70	0.0266	0.518	0.336	0.84
558	274.26	167	32.90	15,180	1.77	46.96	0.445	0.608	0.0450	2.8	11.92	0.0411	0.600	0.439	0.79
559	274.26	203	39.99	15,570	1.81	47.23	0.480	0.640	0.0536	2.9	11.57	0.0490	0.632	0.467	0.70
560	274.26	67	13.20	13,480	1.57	45.15	0.270	0.425	0.0195	2.6	8.02	0.0178	0.413	0.295	0.98
561	314.34	67	13.20	13,930	1.64	44.96	0.259	0.410	0.0191	2.2	5.48	0.0174	0.395	0.234	1.00
562	314.34	108	21.28	14,150	1.66	46.27	0.333	0.500	0.312	2.5	8.31	0.285	0.480	0.313	0.91
563	314.34	134	26.40	14,550	1.71	46.60	0.354	0.525	0.0379	2.65	7.64	0.0347	0.515	0.334	0.89
564	314.34	167	32.90	14,950	1.76	46.87	0.383	0.570	0.0463	2.85	8.44	0.0426	0.540	0.336	0.87
565	314.31	204	40.19	15,480	1.82	47.09	0.436	0.595	0.0548	2.65	11.29	0.0502	0.610	0.420	0.82
567	414.31	108	21.28	13,990	1.68	46.27	0.293	0.445	0.0327	2.3	4.88	0.0299	0.446	0.274	0.87
568	414.31	134	26.40	14,150	1.70	45.93	0.324	0.480	0.0400	2.5	6.10	0.0365	0.480	0.301	1.13
569	414.42	170	33.49	14,440	1.74	46.85	0.368	0.565	0.0505	2.35	7.50	0.0462	0.545	0.350	0.88
570	414.42	204	40.19	14,810	1.78	46.83	0.405	0.600	0.0591	2.4	6.97	0.0540	0.685	0.384	1.06
571	514.42	108	21.28	12,930	1.59	45.99	0.263	0.440	0.0363	2.25	2.79	0.0332	0.420	0.241	0.99
572	514.42	136	26.79	13,940	1.64	46.46	0.306	0.485	0.0429	2.2	3.77	0.0392	0.460	0.290	0.87
573	514.42	168	33.10	14,120	1.73	46.99	0.352	0.525	0.0529	2.2	6.38	0.0484	0.515	0.336	0.71
574	514.42	203	39.99	14,520	1.78	47.07	0.366	0.550	0.0621	2.35	6.11	0.0568	0.540	0.350	0.76
575	514.48	67	13.20	12,640	1.55	43.81	0.203	0.330	0.0220	2.0	0.42	0.0200	0.325	0.176	1.31
581	114.48	108	21.28	16,420	1.82	45.50	0.417	0.615	0.0242	3.25	9.36	0.0221	0.610	0.384	1.17
582	114.50	134	26.40	16,550	1.83	46.38	0.498	0.700	0.0303	3.0	13.52	0.0277	0.660	0.472	0.94
583	114.50	168	33.10	16,290	1.80	46.89	0.535	0.745	0.0390	3.2	15.00	0.0357	0.720	0.517	0.81
589	114.51	203	39.99	15,380	1.70	47.00	0.585	0.775	0.0501	3.3	18.51	0.0458	0.765	0.568	0.94

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TABLE II

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
420	2	0.019	0.0011	0.020	1.90
	3	0.040	0.0023	0.048	1.67
	5	0.083	0.0047	0.085	1.88
	7	0.125	0.0071	0.126	1.84
	9	0.163	0.0092	0.154	1.90
	11	0.211	0.0119	0.252	1.33
	13	0.253	0.0143	0.265	1.50
	17	0.339	0.0191	0.270	1.96
	21	0.424	0.0240	0.304	2.09
	25	0.509	0.0288	0.359	1.97
	29	0.595	0.0336	0.382	2.09
	33	0.680	0.0384	0.417	2.08
	37	0.765	0.0433	0.427	2.26
	39	0.808	0.0457	0.449	2.18
	41	0.851	0.0481	0.452	2.28
	45	0.936	0.0529	0.482	2.23
	47	0.979	0.0553	0.508	2.11
	49	-	0.0565	0.481	2.31
	51	-	0.0565	0.490	2.32
	56	-	0.0565	0.479	2.43

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TABLE III

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
423	2	-	-	-	-
	3	0.014	0.0005	0.014	1.32
	5	0.058	0.0022	0.037	2.10
	7	0.102	0.0038	0.056	2.40
	9	0.145	0.0054	0.095	1.92
	11	0.189	0.0071	0.109	2.16
	13	0.233	0.0087	0.152	1.82
	17	0.321	0.0120	0.193	1.88
	21	0.408	0.0153	0.217	2.08
	25	0.496	0.0185	0.260	2.00
	29	0.584	0.0218	0.278	2.16
	33	0.671	0.0251	0.303	2.20
	37	0.759	0.0284	0.320	2.30
	39	0.803	0.0300	0.352	2.12
	41	0.847	0.0317	0.408	1.76
	43	0.890	0.0333	0.371	2.17
	45	0.934	0.0349	0.396	2.05
	49	-	0.0374	0.349	2.70
	51	-	0.0374	0.359	2.58
	54	-	0.0374	0.221	5.10
	56	-	0.0374	0.371	2.45

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 TABLE IV

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
445	2	0.021	0.0013	0.032	1.44
	3	0.042	0.0026	0.054	1.64
	5	0.085	0.0052	0.091	1.95
	7	0.127	0.0079	0.146	1.73
	9	0.170	0.0105	0.183	1.77
	11	0.212	0.0131	0.213	1.83
	13	0.255	0.0158	0.247	1.83
	15	0.297	0.0185	0.281	1.79
	17	0.340	0.0211	0.293	1.94
	21	0.425	0.0264	0.330	2.05
	25	0.510	0.0317	0.386	1.94
	29	0.596	0.0369	0.412	2.04
	33	0.681	0.0422	0.443	2.05
	37	0.766	0.0475	0.480	2.01
	41	0.851	0.0528	0.488	2.18
	43	0.894	0.0554	0.521	2.01
	45	0.936	0.0581	0.542	1.94
	47	0.979	0.0607	0.533	2.10
	49	-	0.0620	0.532	2.16
	51	-	0.0620	0.580	1.79
	56	-	0.0620	0.483	2.63
	59	-	0.0620	0.531	2.17

58 TABLE V

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
452	2	0.032	0.0027	0.041	2.30
	3	0.053	0.0044	0.086	1.74
	5	0.096	0.0079	0.130	1.98
	7	0.138	0.0113	0.193	1.79
	9	0.180	0.0148	0.228	1.89
	11	0.222	0.0183	0.237	2.22
	13	0.264	0.0217	0.295	1.97
	15	0.306	0.0252	0.322	2.02
	17	0.348	0.0287	0.334	2.19
	21	0.432	0.0356	0.388	2.17
	25	0.516	0.0425	0.420	2.28
	29	0.600	0.0495	0.467	2.21
	33	0.685	0.0564	0.488	2.33
	37	0.769	0.0633	0.527	2.25
	41	0.853	0.0703	0.547	2.33
	43	0.895	0.0737	0.578	2.14
	45	0.937	0.0772	0.592	2.14
	47	0.979	0.0807	0.598	2.20
	49	-	0.0824	0.609	2.15
	51	-	0.0824	0.629	1.97
	56	-	0.0824	0.538	2.87
	59	-	0.0824	0.589	2.33

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TABLE VI

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
517	2.5	0.027	0.0012	-	-
	3	0.048	0.0022	0.009	9.26
	5	0.091	0.0042	0.051	2.87
	7	0.133	0.0061	0.068	3.13
	9	0.175	0.0081	0.106	2.55
	11	0.217	0.0100	0.145	2.21
	13	0.260	0.0120	0.172	2.17
	17	0.344	0.0159	0.217	2.16
	21	0.429	0.0198	0.265	2.08
	25	0.514	0.0237	0.278	2.34
	29	0.598	0.0276	0.333	2.12
	33	0.683	0.0315	0.362	2.13
	37	0.767	0.0354	0.392	2.12
	41	0.852	0.0393	0.418	2.11
	43	0.894	0.0412	0.443	2.01
	45	0.937	0.0432	0.455	2.01
	47	0.979	0.0451	0.501	1.75
	49	-	0.0461	0.498	1.81
	51	-	0.0461	0.446	2.23
	54	-	0.0461	0.281	2.80
	56	-	0.0461	0.406	2.63
	59	-	0.0461	0.444	2.25

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TABLE VII

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
527	2	0.022	0.0006	-	-
	3	0.043	0.0011	0.003	14.2
	7	0.128	0.0033	0.006	20.7
	9	0.171	0.0044	0.051	3.14
	13	0.256	0.0066	0.089	4.54
	17	0.341	0.0087	0.127	2.23
	21	0.426	0.0108	0.157	2.19
	25	0.511	0.0130	0.216	1.78
	29	0.596	0.0152	0.217	2.06
	33	0.681	0.0173	0.233	2.15
	37	0.766	0.0195	0.268	2.02
	41	0.851	0.0216	0.288	2.04
	45	0.936	0.0238	0.295	2.14
	47	0.979	0.0249	0.292	2.30
	49	-	0.0254	0.294	2.33
	51	-	0.0254	0.311	2.15
	54	-	0.0254	0.205	3.76
	56	-	0.0254	0.257	2.80
	59	-	0.0254	0.301	2.26

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TABLE VIII

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
555	2	-	-	0.025	-
	3	0.022	0.0007	0.027	2.20
	5	0.065	0.0020	0.084	2.03
	7	0.109	0.0033	0.129	2.09
	9	0.152	0.0046	0.167	2.16
	11	0.196	0.0059	0.211	2.09
	13	0.239	0.0072	0.239	2.18
	15	0.283	0.0085	0.262	2.28
	17	0.326	0.0098	0.273	2.48
	19	0.370	0.0112	0.304	2.42
	21	0.413	0.0125	0.294	2.86
	25	0.500	0.0151	0.307	3.25
	29	0.587	0.0177	0.344	3.22
	33	0.674	0.0203	0.351	3.61
	37	0.761	0.0230	0.412	3.16
	41	0.848	0.0256	0.436	3.20
	45	0.935	0.0282	0.454	3.28
	47	0.978	0.0295	0.474	3.18
	49	-	0.0302	0.476	3.22
	51	-	0.0302	0.442	3.70
	54	-	0.0302	0.376	4.86
	56	-	0.0302	0.466	3.35
	59	-	0.0302	0.474	3.24

62 TABLE IX

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
556	2	0.016	0.0006	0.060	0.85
	3	0.037	0.0014	0.097	1.20
	5	0.080	0.0029	0.147	1.60
	7	0.123	0.0045	0.203	1.67
	9	0.166	0.0061	0.243	1.78
	11	0.208	0.0076	0.276	1.90
	13	0.251	0.0092	0.294	2.10
	15	0.293	0.0108	0.333	2.05
	17	0.336	0.0124	0.362	2.07
	19	0.379	0.0139	0.380	2.16
	21	0.422	0.0155	0.398	2.24
	25	0.508	0.0186	0.413	2.53
	29	0.593	0.0218	0.454	2.52
	33	0.679	0.0249	0.485	2.55
	37	0.764	0.0280	0.504	2.66
	41	0.850	0.0312	0.518	2.91
	45	0.936	0.0343	0.567	2.55
	47	0.978	0.0359	0.555	2.81
	49	-	0.0367	0.564	2.77
	51	-	0.0367	0.563	2.77
	54	-	0.0367	0.449	4.39
	56	-	0.0367	0.532	3.14
	59	-	0.0367	0.551	2.92

63 TABLE X

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
557	2	0.007	0.0002	0.013	1.49
	3	0.028	0.0008	0.061	1.20
	5	0.072	0.0021	0.106	1.66
	7	0.115	0.0034	0.141	1.93
	9	0.158	0.0046	0.206	1.67
	11	0.201	0.0059	0.232	1.83
	13	0.244	0.0071	0.210	2.54
	15	0.288	0.0084	0.273	2.11
	17	0.331	0.0096	0.304	2.09
	19	0.374	0.0109	0.324	2.15
	21	0.417	0.0119	0.336	2.24
	25	0.504	0.0146	0.359	2.50
	29	0.590	0.0172	0.407	2.39
	33	0.676	0.0197	0.439	2.40
	37	0.763	0.0222	0.462	2.48
	41	0.849	0.0247	0.504	2.34
	45	0.935	0.0272	0.522	2.40
	47	0.978	0.0285	0.514	2.61
	49	-	0.0291	0.521	2.59
	51	-	0.0291	0.501	2.81
	54	-	0.0291	0.394	4.33
	56	-	0.0291	0.514	2.66
	59	-	0.0291	0.501	2.80

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TABLE XI

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
558	2	0.020	0.0001	0.095	0.83
	3	0.042	0.0019	0.139	1.10
	5	0.084	0.0038	0.181	1.61
	7	0.127	0.0057	0.234	1.77
	9	0.170	0.0076	0.281	1.87
	11	0.212	0.0095	0.311	2.00
	13	0.255	0.0114	0.315	2.37
	15	0.297	0.0134	0.371	2.20
	17	0.340	0.0153	0.400	2.18
	19	0.382	0.0172	0.429	2.19
	21	0.425	0.0191	0.445	2.28
	29	0.595	0.0268	0.502	2.56
	33	0.681	0.0306	0.526	2.68
	37	0.766	0.0344	0.561	2.63
	41	0.851	0.0383	0.576	2.75
	45	0.936	0.0421	0.606	2.68
	47	0.979	0.0440	0.606	2.81
	49	-	0.0450	0.610	2.83
	51	-	0.0450	0.635	2.54
	54	-	0.0450	0.508	4.28
	56	-	0.0450	0.574	3.28
	59	-	0.0450	0.593	3.03

65 TABLE XII

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
559	2	0.026	0.0014	0.151	0.74
	3	0.047	0.0025	0.140	1.47
	5	0.068	0.0037	0.219	1.23
	7	0.111	0.0059	0.268	1.53
	9	0.153	0.0082	0.317	1.67
	11	0.195	0.0105	0.360	1.77
	13	0.238	0.0127	0.382	1.96
	15	0.280	0.0150	0.396	2.18
	17	0.322	0.0173	0.435	2.14
	19	0.365	0.0196	0.467	2.13
	21	0.407	0.0218	0.481	2.27
	25	0.492	0.0264	0.503	2.51
	29	0.577	0.0309	0.536	2.59
	33	0.661	0.0354	0.555	2.76
	37	0.746	0.0400	0.598	2.63
	41	0.831	0.0445	0.608	2.82
	45	0.915	0.0490	0.638	2.75
	47	0.958	0.0513	0.635	2.92
	49	-	0.0536	0.644	2.95
	51	-	0.0536	0.664	2.69
	54	-	0.0536	0.569	4.03
	56	-	0.0536	0.624	3.20
	59	-	0.0536	0.640	3.00

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TABLE XIII

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
560	2	-	-	0.016	-
	3	0.003	0.0001	0.005	1.06
	5	0.048	0.0009	0.036	2.37
	7	0.092	0.0018	0.084	1.84
	9	0.136	0.0027	0.122	1.80
	11	0.181	0.0035	0.128	2.26
	13	0.225	0.0044	0.131	2.76
	15	0.269	0.0053	0.211	1.86
	17	0.313	0.0061	0.210	2.17
	19	0.358	0.0065	0.223	2.14
	21	0.402	0.0079	0.273	1.98
	25	0.491	0.0096	0.289	2.24
	29	0.579	0.0113	0.304	2.46
	33	0.667	0.0130	0.337	2.44
	37	0.756	0.0148	0.357	2.54
	41	0.845	0.0165	0.374	2.64
	45	0.933	0.0182	0.428	2.33
	47	0.978	0.0191	0.402	2.72
	49	-	0.0195	0.423	2.56
	51	-	0.0195	0.402	2.78
	54	-	0.0195	0.263	5.25
	56	-	0.0195	0.370	3.19
	59	-	0.0195	0.422	2.57

67 TABLE XIV

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
561	2	-	-	-	-
	3	-	-	-	-
	5	0.044	0.0008	-	-
	7	0.088	0.0017	0.101	1.17
	9	0.133	0.0025	0.157	1.06
	11	0.177	0.0034	0.151	1.49
	13	0.221	0.0042	0.153	1.84
	15	0.266	0.0051	0.178	1.84
	17	0.310	0.0059	0.220	1.65
	19	0.355	0.0068	0.237	1.72
	21	0.399	0.0076	0.242	1.88
	25	0.488	0.0093	0.249	2.22
	29	0.577	0.0110	0.294	2.09
	33	0.666	0.0127	0.324	2.10
	37	0.755	0.0144	0.344	2.18
	41	0.844	0.0161	0.366	2.22
	45	0.933	0.0178	0.407	2.06
	47	0.978	0.0187	0.399	2.24
	49	-	0.0191	0.415	2.15
	51	-	0.0191	0.382	2.46
	54	-	0.0191	0.289	3.76
	56	-	0.0191	0.345	2.89
	59	-	0.0191	0.381	2.48

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TABLE XV

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
562	2	0.006	0.0002	0.059	0.22
	3	0.027	0.0009	0.073	0.85
	5	0.071	0.0022	0.114	1.34
	7	0.114	0.0036	0.144	1.66
	9	0.157	0.0049	0.205	1.49
	11	0.200	0.0063	0.236	1.58
	13	0.244	0.0076	-	-
	15	0.287	0.0090	0.274	1.87
	17	0.330	0.0103	0.316	1.76
	19	0.373	0.0117	0.329	1.88
	21	0.416	0.0129	0.351	1.90
	25	0.502	0.0157	0.344	2.37
	29	0.589	0.0184	0.399	2.20
	33	0.676	0.0211	0.428	2.25
	37	0.762	0.0238	0.430	2.52
	41	0.848	0.0265	0.459	2.51
	45	0.935	0.0291	0.488	2.47
	47	0.978	0.0305	0.498	2.47
	49	-	0.0312	0.559	1.98
	51	-	0.0312	0.493	2.59
	54	-	0.0312	0.697	1.09
	56	-	0.0312	0.437	3.24
	59	-	0.0312	0.487	2.65

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TABLE XVI

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
563	2	0.013	0.0005	0.037	0.99
	3	0.034	0.0013	0.064	1.49
	5	0.077	0.0029	0.096	2.17
	7	0.120	0.0046	0.148	2.06
	9	0.163	0.0062	0.136	3.07
	11	0.206	0.0078	0.233	2.02
	13	0.249	0.0094	0.250	2.23
	15	0.292	0.0111	0.270	2.37
	17	0.334	0.0127	0.325	2.09
	19	0.378	0.0143	0.349	2.11
	21	0.421	0.0159	0.371	2.15
	25	0.506	0.0192	0.394	2.35
	29	0.592	0.0225	0.420	2.48
	33	0.678	0.0257	0.456	2.46
	37	0.763	0.0290	0.475	2.57
	41	0.849	0.0322	0.491	2.70
	45	0.935	0.0355	0.524	2.61
	47	0.978	0.0371	0.524	2.73
	49	-	0.0379	0.530	2.72
	51	-	0.0379	0.542	2.61
	54	-	0.0379	0.417	4.31
	56	-	0.0379	0.499	3.09
	59	-	0.0379	0.515	2.90

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TABLE XVII

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
564	2	0.019	0.0009	0.055	1.16
	3	0.040	0.0019	0.082	1.62
	5	0.083	0.0038	0.152	1.67
	7	0.125	0.0058	0.194	1.89
	9	0.168	0.0078	0.243	1.91
	11	0.211	0.0097	0.273	2.05
	13	0.253	0.0117	0.302	2.14
	15	0.295	0.0137	0.323	2.28
	17	0.339	0.0157	0.358	2.22
	19	0.381	0.0176	0.391	2.19
	21	0.424	0.0196	0.410	2.25
	25	0.509	0.0236	0.424	2.56
	29	0.595	0.0275	0.465	2.54
	33	0.680	0.0315	0.430	3.36
	37	0.765	0.0354	0.518	2.67
	41	0.851	0.0394	0.540	2.73
	45	0.936	0.0433	0.540	3.02
	47	0.979	0.0453	0.566	2.84
	49	-	0.0462	0.583	2.71
	51	-	0.0462	0.592	2.61
	54	-	0.0462	0.470	4.28
	56	-	0.0462	0.563	2.94
	59	-	0.0462	0.571	3.85

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TABLE XVIII

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
565	2	0.023	0.0013	0.077	1.19
	3	0.044	0.0024	0.120	1.39
	5	0.087	0.0048	0.135	2.39
	7	0.129	0.0071	0.237	1.80
	9	0.172	0.0095	0.305	1.69
	11	0.214	0.0118	0.326	1.92
	13	0.257	0.0141	0.364	1.95
	15	0.299	0.0164	0.386	2.07
	17	0.342	0.0187	0.422	2.04
	19	0.384	0.0211	0.441	2.13
	21	0.427	0.0234	0.451	2.28
	25	0.512	0.0281	0.479	2.46
	29	0.597	0.0327	0.518	2.45
	33	0.681	0.0374	0.536	2.62
	37	0.766	0.0420	0.567	2.62
	41	0.851	0.0467	0.589	2.67
	45	0.936	0.0513	0.619	2.60
	47	0.979	0.0537	0.620	2.71
	49	-	0.0548	0.632	2.64
	51	-	0.0548	0.629	2.67
	54	-	0.0548	0.519	4.20
	56	-	0.0548	0.613	2.86
	59	-	0.0548	0.624	2.74

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TABLE XIX

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
567	2	0.006	0.0002	0.024	0.45
	3	0.027	0.0009	0.051	0.97
	5	0.071	0.0023	0.056	2.26
	7	0.114	0.0037	0.098	1.99
	9	0.157	0.0051	0.140	1.83
	11	0.200	0.0066	0.162	1.97
	13	0.243	0.0080	0.218	1.66
	15	0.287	0.0094	0.234	1.79
	17	0.330	0.0108	0.256	1.83
	19	0.373	0.0122	0.275	1.88
	21	0.416	0.0136	0.296	1.89
	25	0.503	0.0164	0.313	2.12
	29	0.589	0.0193	0.356	2.06
	33	0.676	0.0221	0.380	2.13
	37	0.762	0.0249	0.408	2.15
	41	0.849	0.0277	0.413	2.34
	45	0.935	0.0306	0.448	2.25
	47	0.978	0.0320	0.445	2.38
	49	-	0.0327	0.468	2.22
	51	-	0.0327	0.446	2.42
	54	-	0.0327	0.346	3.68
	56	-	0.0327	0.435	2.54
	59	-	0.0327	0.431	2.57

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TABLE XX

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
568	2	-	-	0.005	-
	3	0.020	0.0008	0.014	3.22
	5	0.064	0.0026	0.070	1.96
	7	0.107	0.0043	0.125	1.74
	9	0.151	0.0060	0.149	2.00
	11	0.194	0.0078	0.206	1.74
	13	0.238	0.0095	0.240	1.76
	15	0.282	0.0113	0.244	2.04
	17	0.325	0.0130	0.274	2.02
	19	0.369	0.0148	0.300	2.02
	21	0.412	0.0165	0.326	2.00
	25	0.499	0.0200	0.344	2.24
	29	0.586	0.0235	0.386	2.21
	33	0.673	0.0270	0.410	2.40
	37	0.761	0.0304	0.428	2.32
	41	0.848	0.0339	0.468	2.31
	45	0.935	0.0374	0.481	2.42
	47	0.978	0.0392	0.428	2.57
	49	-	0.0400	0.499	2.41
	51	-	0.0400	0.496	2.44
	54	-	0.0400	0.364	4.20
	56	-	0.0400	0.463	2.79
	59	-	0.0400	0.492	2.48

TABLE XXI

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Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
569	2	0.018	0.0009	0.054	0.93
	3	0.039	0.0020	0.076	1.39
	5	0.082	0.0042	0.129	1.62
	7	0.125	0.0063	0.173	1.75
	9	0.168	0.0085	0.224	1.71
	11	0.210	0.0106	0.254	1.82
	13	0.253	0.0128	0.278	1.94
	15	0.296	0.0149	0.288	2.17
	17	0.338	0.0171	0.350	1.86
	19	0.381	0.0192	0.357	2.04
	21	0.424	0.0214	0.380	2.06
	25	0.509	0.0257	0.386	2.43
	29	0.594	0.0300	0.438	2.29
	33	0.680	0.0343	0.464	2.38
	37	0.765	0.0387	0.492	2.40
	41	0.851	0.0430	0.510	2.49
	45	0.936	0.0473	0.558	2.27
	47	0.479	0.0494	0.563	2.33
	49	-	0.0505	0.556	2.46
	51	-	0.0505	0.573	2.29
	54	-	0.0505	0.437	3.95
	56	-	0.0505	0.523	2.80
	59	-	0.0505	0.545	2.57

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TABLE XXII

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
570	2	0.018	0.0011	0.068	0.83
	3	0.039	0.0023	0.090	1.35
	5	0.082	0.0048	0.169	1.38
	7	0.124	0.0074	0.209	1.62
	9	0.167	0.0099	0.247	1.76
	11	0.210	0.0124	0.282	1.85
	13	0.253	0.0149	0.290	2.14
	15	0.295	0.0124	0.333	2.06
	17	0.338	0.0200	0.374	1.97
	19	0.381	0.0224	0.389	2.09
	21	0.423	0.0250	0.413	2.11
	25	0.509	0.0301	0.417	2.50
	29	0.594	0.0351	0.472	2.35
	33	0.680	0.0401	0.504	2.37
	37	0.765	0.0452	0.535	2.38
	41	0.851	0.0502	0.553	2.47
	45	0.936	0.0553	0.599	2.26
	47	0.979	0.0578	0.601	2.35
	49	-	0.0591	0.540	3.09
	51	-	0.0591	0.608	2.34
	54	-	0.0591	0.485	3.85
	56	-	0.0591	0.574	2.69
	59	-	0.0591	0.587	2.55

TABLE XXIII

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Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
571	2	-	-	0.014	-
	3	0.022	0.0008	0.024	1.47
	5	0.065	0.0024	0.066	1.54
	7	0.109	0.0039	0.044	1.75
	9	0.152	0.0055	0.120	1.88
	11	0.195	0.0071	0.159	1.75
	13	0.239	0.0087	0.177	1.88
	15	0.282	0.0103	0.194	1.99
	17	0.326	0.0118	0.225	1.90
	19	0.369	0.0134	0.229	2.11
	21	0.413	0.0150	0.250	2.11
	25	0.500	0.0182	0.269	2.32
	29	0.587	0.0213	0.321	2.13
	33	0.674	0.0245	0.343	2.22
	37	0.761	0.0277	0.367	2.26
	41	0.848	0.0308	0.390	2.30
	45	0.935	0.0340	0.424	2.21
	47	0.978	0.0356	0.435	2.21
	49	-	0.0363	0.450	2.13
	51	-	0.0363	0.424	2.37
	54	-	0.0363	0.315	3.79
	56	-	0.0363	0.413	2.48
	59	-	0.0363	0.423	2.38

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TABLE XXIV

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
572	2	0.010	0.0004	0.042	0.45
	3	0.031	0.0014	0.048	1.24
	5	0.075	0.0032	0.099	1.34
	7	0.118	0.0050	0.126	1.63
	9	0.161	0.0069	0.172	1.54
	11	0.204	0.0087	0.203	1.60
	13	0.247	0.0106	0.222	1.73
	15	0.290	0.0124	0.235	1.89
	17	0.333	0.0143	0.287	1.66
	19	0.376	0.0161	0.280	1.95
	21	0.419	0.0180	0.304	1.94
	25	0.505	0.0217	0.320	2.17
	29	0.591	0.0254	0.359	2.15
	33	0.677	0.0290	0.400	2.07
	37	0.763	0.0327	0.420	2.16
	41	0.849	0.0364	0.438	2.24
	45	0.935	0.0401	0.466	2.22
	47	0.978	0.0420	0.484	2.16
	49	-	0.0429	0.486	2.19
	51	-	0.0429	0.502	2.05
	54	-	0.0429	0.587	1.46
	56	-	0.0429	0.457	2.46
	59	-	0.0429	0.468	2.36

78 TABLE XXV

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
573	2	0.021	0.0011	0.049	1.00
	3	0.042	0.0022	0.077	1.25
	5	0.085	0.0045	0.127	1.43
	7	0.127	0.0067	0.168	1.55
	9	0.170	0.0090	0.205	1.63
	11	0.213	0.0112	0.236	1.70
	13	0.255	0.0135	0.261	1.79
	15	0.298	0.0158	0.285	1.86
	17	0.340	0.0180	0.313	1.86
	19	0.383	0.0203	0.330	1.94
	21	0.425	0.0225	0.341	2.05
	25	0.511	0.0270	0.370	2.18
	29	0.596	0.0315	0.405	2.21
	33	0.681	0.0360	0.433	2.26
	37	0.766	0.0405	0.481	2.10
	41	0.851	0.0450	0.491	2.25
	45	0.936	0.0495	0.520	2.22
	47	0.979	0.0518	0.522	2.31
	49	-	0.0529	0.430	3.42
	51	-	0.0529	0.547	2.14
	54	-	0.0529	0.479	2.81
	56	-	0.0529	0.512	2.46
	59	-	0.0529	0.518	2.40

TABLE XXVI

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Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
574	2	0.023	0.0014	0.046	1.35
	3	0.044	0.0027	0.070	1.67
	5	0.086	0.0054	0.121	1.80
	7	0.129	0.0080	0.174	1.77
	9	0.171	0.0106	0.208	1.90
	11	0.214	0.0133	0.250	1.86
	13	0.256	0.0159	0.273	1.99
	15	0.299	0.0186	0.293	2.11
	17	0.341	0.0212	0.334	1.99
	19	0.384	0.0239	0.343	2.16
	21	0.426	0.0265	0.360	2.23
	25	0.511	0.0317	0.382	2.45
	29	0.596	0.0370	0.421	2.45
	33	0.681	0.0423	0.475	2.26
	37	0.766	0.0476	0.493	2.38
	41	0.851	0.0528	0.527	2.31
	45	0.936	0.0581	0.546	2.37
	47	0.978	0.0607	0.551	2.44
	49	-	0.0621	0.496	3.11
	51	-	0.0621	0.541	2.60
	54	-	0.0621	0.451	3.72
	56	-	0.0621	0.545	2.56
	59	-	0.0621	0.561	2.40

TABLE XXVII

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Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
575	2	-	-	-	-
	3	-	-	-	-
	5	0.018	0.0004	0.017	1.12
	7	0.064	0.0014	0.030	2.12
	9	0.110	0.0024	0.087	1.17
	11	0.155	0.0034	0.083	1.74
	13	0.201	0.0044	0.109	1.67
	15	0.247	0.0054	0.122	1.82
	17	0.292	0.0064	0.153	1.66
	19	0.338	0.0074	0.174	1.64
	21	0.384	0.0084	0.186	1.72
	25	0.475	0.0104	0.221	1.72
	29	0.566	0.0124	0.246	1.79
	33	0.658	0.0145	0.251	2.02
	37	0.749	0.0165	0.278	2.00
	41	0.840	0.0185	0.306	1.97
	45	0.932	0.0205	0.331	1.96
	47	0.977	0.0215	0.341	1.96
	49	-	0.0220	0.333	2.08
	51	-	0.0220	0.324	2.17
	54	-	0.0220	0.231	3.45
	56	-	0.0220	0.325	2.16
	59	-	0.0220	0.332	2.09

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TABLE XXVIII

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
581	2	-	-	0.047	-
	3	0.011	0.0003	0.083	0.58
	5	0.055	0.0013	0.131	1.94
	7	0.099	0.0024	0.187	2.28
	9	0.143	0.0035	0.225	2.60
	11	0.187	0.0045	0.247	3.03
	13	0.231	0.0056	0.228	4.17
	15	0.275	0.0066	0.316	3.18
	17	0.319	0.0077	0.358	3.05
	19	0.363	0.0088	0.385	3.09
	21	0.907	0.0098-	0.420	3.00
	25	0.495	0.0120	0.430	3.52
	29	0.582	0.0141	0.486	3.31
	33	0.692	0.067	0.534	3.26
	37	0.758	0.0183	0.559	3.23
	41	0.846	0.205	0.591	3.17
	45	0.934	0.0226	0.612	3.21
	47	0.978	0.0237	0.612	3.37
	49	-	0.0242	0.619	3.35
	51	-	0.0242	0.636	3.11
	54	-	0.0242	0.562	4.23
	56	-	0.0242	0.607	3.51
	59	-	0.0242	0.616	3.39

TABLE XXIX

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Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
582	2	0.008	0.0003	0.075	0.68
	3	0.030	0.0009	0.124	1.40
	5	0.073	0.0022	0.191	2.05
	7	0.116	0.0035	0.270	2.12
	9	0.159	0.0048	0.303	2.44
	11	0.202	0.0061	0.350	2.51
	13	0.245	0.0074	0.384	2.64
	15	0.288	0.0088	0.416	2.72
	17	0.332	0.0101	0.481	2.40
	19	0.375	0.0114	0.490	2.62
	21	0.418	0.0127	0.529	2.51
	25	0.504	0.0153	0.521	3.13
	29	0.590	0.0179	0.569	3.03
	33	0.677	0.0205	0.644	2.53
	37	0.763	0.0231	0.644	2.87
	41	0.849	0.0257	0.652	3.09
	45	0.935	0.0284	0.667	3.16
	47	0.978	0.0297	0.700	2.88
	49	-	0.0303	0.704	2.87
	51	-	0.0303	0.728	2.56
	54	-	0.0303	0.616	4.26
	56	-	0.0303	0.639	3.85
	59	-	0.0303	0.632	3.98

TABLE XXX

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Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
583	2	0.019	0.007	0.116	1.24
	3	0.040	0.0016	0.173	1.65
	5	0.083	0.0032	0.265	1.98
	7	0.126	0.0049	0.315	2.35
	9	0.168	0.0066	0.367	2.50
	11	0.211	0.0082	0.914	2.58
	13	0.254	0.0099	0.439	2.81
	15	0.296	0.0116	0.468	2.92
	17	0.339	0.0132	0.508	2.85
	19	0.382	0.0149	0.536	2.87
	21	0.424	0.0166	0.593	2.53
	25	0.509	0.0199	0.583	3.19
	29	0.595	0.0232	0.619	3.22
	33	0.680	0.0266	0.662	3.06
	37	0.765	0.0299	0.664	3.92
	41	0.851	0.0332	0.677	3.60
	45	0.936	0.0366	0.733	3.03
	47	0.979	0.0382	0.744	3.00
	49	-	0.0391	0.744	3.06
	51	-	0.0391	0.738	3.16
	54	-	0.0391	0.673	4.33
	56	-	0.0391	0.717	3.53
	59	-	0.0391	0.718	3.50

84 TABLE XXXI

Run No.	Distance from Inlet, In.	Fractional Length in Boiling	Quality	Steam Volume Fraction	Velocity Ratio
589	2	0.021	0.0011	0.155	1.28
	3	0.043	0.0021	0.237	1.50
	5	0.085	0.0043	0.321	1.98
	7	0.128	0.0064	0.379	2.32
	9	0.170	0.0085	0.415	2.66
	11	0.213	0.0107	0.457	2.80
	13	0.255	0.0128	0.492	2.93
	15	0.298	0.0149	0.501	3.31
	17	0.340	0.0171	0.572	2.85
	19	0.383	0.0192	0.577	3.15
	21	0.426	0.0213	0.629	2.82
	25	0.511	0.0256	0.644	3.19
	29	0.596	0.0299	0.679	3.19
	33	0.681	0.0341	0.706	3.23
	37	0.766	0.0384	0.732	3.20
	41	0.851	0.0426	0.750	3.25
	45	0.936	0.0969	0.773	3.17
	47	0.979	0.0490	0.767	3.44
	49	-	0.0501	0.741	4.03
	51	-	0.0501	0.796	2.96
	54	-	0.0501	0.692	5.15
	56	-	0.0501	0.725	4.39
	59	-	0.0501	0.750	3.85

APPENDIX II(2)

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DERIVATION OF VELOCITY RATIO C_g/C_ℓ

The continuity equations for flow in a pipe where both vapor and liquid components exist are:

$$W_g = C_g A_g \rho_g \quad ; \quad (1)$$

$$W_\ell = C_\ell A_\ell \rho_\ell \quad ; \quad (2)$$

where W_g = weight flow of vapor, W_ℓ = weight flow of liquid, A_g = flow area for vapor, A_ℓ = flow area for liquid, C_g = velocity of vapor, C_ℓ = velocity of liquid, ρ_g = density of vapor, and ρ_ℓ = density of liquid.

The area relationships are:

$$A_g = \alpha A \quad ;$$

$$A_\ell = (1 - \alpha) A \quad ,$$

where α = volume fraction of vapor and A = total area.

Substituting and dividing (1) and (2):

$$\frac{W_g}{W_\ell} = \frac{\alpha A C_g \rho_g}{(1 - \alpha) A C_\ell \rho_\ell} = \left(\frac{\alpha}{1 - \alpha} \right) \left(\frac{C_g}{C_\ell} \right) \left(\frac{\rho_g}{\rho_\ell} \right) \quad . \quad (3)$$

Since

$$\frac{\rho_g}{\rho_\ell} = \frac{v_\ell}{v_g} \quad \text{and} \quad \frac{W_g}{W_\ell} = \frac{X}{1 - X} \quad ,$$

then substituting in (3) and rearranging:

$$\frac{C_g}{C_\ell} = \left(\frac{X}{1 - X} \right) \left(\frac{1 - \alpha}{\alpha} \right) \left(\frac{v_g}{v_\ell} \right) \quad . \quad (4)$$

86 APPENDIX III⁽¹¹⁾

From a heat balance

$$Q_t = Q_\ell + Q_s \quad ;$$

$$Q_s = Q_t - Q_\ell \quad .$$

Since

$$X_{\text{ex}} = \frac{Q_t - Q_\ell}{W_t h_{\text{fg}}} \quad ,$$

then

$$Q_t = X_{\text{ex}} W_t h_{\text{fg}} + Q_\ell = X_{\text{ex}} W_t h_{\text{fg}} + W_t C_p \Delta T \quad .$$

Since

$$X_{\text{ex}} = \frac{1}{1 + \left(\frac{C_\ell}{C_g} \right) \left(\frac{v_g}{v_\ell} \right) \left(\frac{1}{\alpha_{\text{ex}}} - 1 \right)} + W_t C_p \Delta T \quad ,$$

the power density would then be

$$\frac{Q_t}{V} = \frac{W_t h_{\text{fg}}}{V \left\{ 1 + \left(\frac{C_\ell}{C_g} \right)_{\text{ex}} \left(\frac{v_g}{v_\ell} \right) \left(\frac{1}{\alpha_{\text{ex}}} - 1 \right) \right\}} + \frac{W_t C_p \Delta T}{V} \quad .$$

By definition

$$\frac{W_t}{A} = \rho V_{\text{in}} \quad \text{and} \quad V = LA \quad ,$$

so

$$\begin{aligned} \frac{Q_t}{V} &= \frac{W_t h_{\text{fg}}}{LA \left[1 + \left(\frac{C_\ell}{C_g} \right)_{\text{ex}} \left(\frac{v_g}{v_\ell} \right) \left(\frac{1}{\alpha_{\text{ex}}} - 1 \right) \right]} + \frac{W_t C_p \Delta T}{LA} \\ &= \frac{h_{\text{fg}} \rho V_{\text{in}}}{L \left[1 + \left(\frac{C_\ell}{C_g} \right)_{\text{ex}} \left(\frac{v_g}{v_\ell} \right) \left(\frac{1}{\alpha_{\text{ex}}} - 1 \right) \right]} + \frac{V_{\text{in}} \rho C_p \Delta T}{L} \end{aligned}$$

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APPENDIX IV

If ℓ' = any distance from beginning of boiling length,

$$\bar{\alpha}_{bl} = \frac{1}{L_b} \int_0^{L_b} \alpha d\ell' \quad .$$

Now

$$\frac{dX}{d\ell'} = K = \text{a constant} \quad ,$$

so

$$\bar{\alpha}_{bl} = \frac{1}{X_{ex}} \int_0^{X_{ex}} \alpha dX \quad .$$

But

$$\alpha = \frac{1}{\left(\frac{C_g}{C_\ell}\right) \left(\frac{v_\ell}{v_g}\right) \left(\frac{1}{X} - 1\right) + 1}$$

so that

$$\begin{aligned} \bar{\alpha}_{bl} &= \frac{1}{X_{ex}} \int_0^{X_{ex}} \frac{1}{\left(\frac{C_g}{C_\ell}\right) \left(\frac{v_\ell}{v_g}\right) \left(\frac{1}{X} - 1\right) + 1} dX \\ &= \frac{1}{X_{ex}} \int_0^{X_{ex}} \frac{X dX}{\left(\frac{C_g}{C_\ell}\right) \left(\frac{v_\ell}{v_g}\right) + X \left[1 - \left(\frac{C_g}{C_\ell}\right) \left(\frac{v_\ell}{v_g}\right)\right]} \quad . \end{aligned}$$

Let

$$\phi = \left(\frac{C_g}{C_\ell}\right) \left(\frac{v_\ell}{v_g}\right) \quad ;$$

then

$$\bar{\alpha}_{bl} = \frac{1}{X_{ex}} \int_0^{X_{ex}} \frac{X dX}{\phi + (1 - \phi) X} \quad .$$

Accordingly,

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$$\begin{aligned}
 \bar{\alpha}_{b1} &= \frac{1}{X_{ex}} \left\{ \frac{X}{(1-\phi)} - \frac{\phi}{(1-\phi)^2} \ln [\phi + (1-\phi) X] \right\} \Bigg|_0^{X_{ex}} \\
 &= \frac{1}{X_{ex}} \left\{ \frac{X_{ex}}{1-\phi} - \frac{\phi}{(1-\phi)^2} \ln [\phi + (1-\phi) X_{ex}] + \frac{\phi}{(1-\phi)^2} \ln \phi \right\} \\
 &= \frac{1}{X_{ex}} \left(\frac{X_{ex}}{1-\phi} - \frac{\phi}{(1-\phi)^2} \left\{ \ln [\phi + (1-\phi) X_{ex}] - \ln \phi \right\} \right) \\
 &= \frac{1}{X_{ex}} \left\{ \frac{X_{ex}}{1-\phi} - \frac{\phi}{(1-\phi)^2} \ln \left[1 + \frac{(1-\phi)}{\phi} X_{ex} \right] \right\} \\
 &= \frac{1}{1-\phi} - \frac{\phi}{(1-\phi)^2 X_{ex}} \ln \left[1 + \frac{(1-\phi) X_{ex}}{\phi} \right] .
 \end{aligned}$$

But

$$X_{ex} = \frac{1}{1 + \left(\frac{C_\ell}{C_g} \right)_{ex} \left(\frac{v_g}{v_\ell} \right) \left(\frac{1}{\alpha_{ex}} - 1 \right)} ;$$

so

$$\begin{aligned}
 \bar{\alpha}_{b1} &= \frac{1}{1 - \left(\frac{C_g}{C_\ell} \right) \left(\frac{v_\ell}{v_g} \right)} - \frac{\left(\frac{C_g}{C_\ell} \right) \left(\frac{v_\ell}{v_g} \right)}{\left[1 - \left(\frac{C_g}{C_\ell} \right) \left(\frac{v_\ell}{v_g} \right) \right]^2 \left[\frac{1}{1 + \left(\frac{C_\ell}{C_g} \right)_{ex} \left(\frac{v_g}{v_\ell} \right) \left(\frac{1}{\alpha_{ex}} - 1 \right)} \right]} \\
 &\quad \ln \left[1 + \frac{\left[1 - \left(\frac{C_g}{C_\ell} \right) \left(\frac{v_\ell}{v_g} \right) \right] \left[\frac{1}{1 + \left(\frac{C_\ell}{C_g} \right) \left(\frac{v_g}{v_\ell} \right) \left(\frac{1}{\alpha_{ex}} - 1 \right)} \right]}{\left(\frac{C_g}{C_\ell} \right) \left(\frac{v_\ell}{v_g} \right)} \right] .
 \end{aligned}$$

Since:

$$\alpha = \frac{\frac{v_g}{v_\ell}}{\left(\frac{C_g}{C_\ell} \right) \left(\frac{1}{X} - 1 \right) + \frac{v_g}{v_\ell}}$$

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$$X_{loc} = \frac{l'}{L_b} X_{ex} = \frac{l'}{L_b} \left[\frac{1}{1 + \left(\frac{C_l}{C_g} \right)_{ex} \left(\frac{v_g}{v_l} \right) \left(\frac{1}{\alpha_{ex}} - 1 \right)} \right]$$

then

$$\alpha = \frac{\frac{v_g}{v_l}}{\left(\frac{C_g}{C_l} \right) \left\{ \frac{1}{\frac{l'}{L_b} \left[\frac{1}{1 + \left(\frac{C_l}{C_g} \right)_{ex} \left(\frac{v_g}{v_l} \right) \left(\frac{1}{\alpha_{ex}} - 1 \right)} \right]} - 1 \right\} + \frac{v_g}{v_l}}$$

then

$$\frac{\alpha}{\alpha_{bl}} = \frac{\frac{v_g}{v_l} \left(\frac{C_g}{C_l} \right) \left[\frac{1}{\frac{l'}{L_b} \left[\frac{1}{1 + \left(\frac{C_l}{C_g} \right)_{ex} \left(\frac{v_g}{v_l} \right) \left(\frac{1}{\alpha_{ex}} - 1 \right)} \right]} - 1 \right] + \frac{v_g}{v_l}}{\frac{1}{1 - \left(\frac{C_g}{C_l} \right) \left(\frac{v_l}{v_g} \right)} \left[1 - \left(\frac{C_g}{C_l} \right) \left(\frac{v_l}{v_g} \right) \right]^2 \left[\frac{1}{1 + \left(\frac{C_l}{C_g} \right)_{ex} \left(\frac{v_g}{v_l} \right) \left(\frac{1}{\alpha_{ex}} - 1 \right)} \right] \ln e \left\{ 1 + \left[\frac{1 - \left(\frac{C_g}{C_l} \right) \left(\frac{v_l}{v_g} \right)}{\left(\frac{C_g}{C_l} \right) \left(\frac{v_l}{v_g} \right)} \right] \left[\frac{1}{1 + \left(\frac{C_l}{C_g} \right)_{ex} \left(\frac{v_g}{v_l} \right) \left(\frac{1}{\alpha_{ex}} - 1 \right)} \right] \right\} \right\}}$$