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**DEVELOPING TWO-PHASE
FLOW IN TUBES AND ANNULI**

U. S. ATOMIC ENERGY COMMISSION
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DEVELOPING TWO-PHASE FLOW IN TUBES AND ANNULI

PART I: EXPERIMENTAL RESULTS, CIRCULAR TUBE

E. Janssen and J. A. Kervinen

PART II: ANALYTICAL STUDIES, TUBES AND ANNULI

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INTRODUCTION

The heat transfer mechanism under flow boiling conditions is a very efficient one, characterized by very high values for the heat transfer coefficient. As the flow moves along the channel, different regimes of boiling occur, each depending upon mass velocity, local quality, and local heat flux, but also upon conditions upstream. These different regimes, in the order of their occurrence, are commonly called bubbly, slug or transition, and annular or annular dispersed. There is some question whether the slug regime actually occurs under boiling conditions when the heat transfer rate is above some threshold value. At qualities approaching 100 percent, the annular regime gives way to a mist or fog flow. This last item is of only limited interest, and will not be considered here.

All of these regimes have been described in detail by many writers. The one thing which the regimes have in common is a high value for the heat transfer coefficient. But if the heat flux is increased without limit, at some point the heat transfer mechanism associated with each regime breaks down, the value of the heat transfer coefficient drops (more or less abruptly, depending on the regime), and the surface temperature rises.

Our purpose here is to achieve a better understanding of these regimes under the developing conditions in which they occur, in order that we may accomplish the highest possible heat transfer rates without the heat transfer mechanisms breaking down. We therefore set as one of our objectives for the work reported in Part I, the measurement of both fully-developed and developing two-phase flow in a single channel, over a range of qualities spanning the several regimes. As the regime of most interest in boiling water reactors is the annular regime, we set as a second objective an analysis of the annular regime, reported in Part II, which would permit some generalization of the results, and extension to other more complex channels. The analysis would hopefully lead eventually to prediction of the "crisis" point at which boiling heat transfer in the annular regime would break down.

PART I

EXPERIMENTAL RESULTS, CIRCULAR TUBE
E. Janssen and J.A. Kervinen

1. SUMMARY, PART I

Tests were run in a 0.68 inch i.d. tube test section, with steam water at 1000 psia flowing vertically upward. Measurements were made of the flow in the annular region next to the wall (the film region), by an isokinetic sampling technique, using concentric splitters which split off the sample flow from the rest of the flow. Film thickness was measured using a conductivity probe. Pressure drop was measured under both adiabatic and boiling conditions. The results showed that:

1. There are subcooled voids next to the wall for $\bar{X}$ near zero.
2. The liquid phase tends to concentrate close to the wall at higher values of $\bar{X}$.
3. The mass flow rate in a constant thickness zone next to the wall is greater under adiabatic conditions than under either single phase or boiling conditions for all $\bar{X}$.
4. Significant radial transfer of mass (as much as 5% of the total mass flowing) takes place from the interior region to the zone next to the wall as the flow moves from the end of the heated length to two feet past the end.
5. The local quality in the zone next to the wall, under boiling conditions, is consistently above the local quality under adiabatic conditions. The fraction of vapor carried in the film decreases with increasing distance past the end of the heated length.
6. For $\bar{X} \leq 0.15$, the two-phase flow is essentially fully developed in the first two feet past the end of the heated length. For $\bar{X} > 0.29$, the flow may not become fully developed in the first eight feet past the end of the heated length.
7. The relative sample flow rate $\dot{W}_s/\dot{W}$ under both boiling and adiabatic conditions is nearly independent of $\bar{G}$ for low values of $\bar{X}$. However, for $\bar{X} > 0.05$ to 0.12, $\dot{W}_s/\dot{W}$ is flow dependent, being higher at lower values of $\bar{G}$.
8. The subcooled voids in the zone next to the wall for $\bar{X}$ near zero are too fine to be detected by the conductivity probe.
9. The observations of flow regime are in essential agreement with the observations of Bergles, et al.⁸
10. The film thickness measurements are in qualitative agreement with the results obtained by Bergles, et al.⁸ and show similar trends.
11. The film thickness at $\bar{G} > 0.5 \times 10^6$ lb/h-ft² under boiling conditions is greater than under adiabatic conditions except for $\bar{X}$ near CHF.
12. The film thickness under both boiling and adiabatic conditions increases with increasing $\bar{G}$ for $\bar{X} < \sim 0.18$ to 0.24, and decreases with increasing $\bar{G}$ for $\bar{X} > \sim 0.22$ to 0.26.
13. The film flow rate at $\bar{G} = 0.5 \times 10^6$ lb/h-ft² is less under boiling conditions than under adiabatic conditions. The film flow rate at $\bar{G} \geq 1.0 \times 10^6$ lb/h-ft² is greater under boiling conditions (in spite of higher voids) than under adiabatic conditions, except for $\bar{X}$ near CHF.
14. The ratio of adiabatic two-phase to single phase frictional pressure drop is 25% to 35% below the Martinelli-Nelson value.⁹

2. CIRCULAR TUBE TEST SECTION

The circular tube test section shown in Figure 1 was designed and built specially for the measurement of developing two-phase flow. It has an inside diameter of 0.683 inch, and has various points of attachment for the electrical power leads so that measurements may be made either at the end of the heated length or at various distances past the end of the heated length. The different possible arrangements are:

Heated Length (ft)	Distance from Heated Length to Exit End of Tube (ft)
15.8	8
4	4
6	2
8	0

Figure 1. Circular Tube Test Section

2.1 SETUP NO. 1

The flow at the exit end of the tube can be divided by means of a concentric cylindrical flow splitter into an inner zone and an outer zone, which in an annular flow regime correspond approximately to the core region and the film region, respectively. This setup with flow splitter in place is shown in Figure 2 and is hereinafter referred to as Setup No. 1.

Static pressure taps located on the wall and on the centerline at the leading edge of the splitter are used to adjust the flow in the outer zone so that the flow at the leading edge is "isokinetic." The flow is presumed to be isokinetic (i.e., unchanged by the means used to measure it) when the static pressures on the wall and centerline are equal. Three different diameter splitters are used in order to traverse the film region. The annular clearance between the largest diameter splitter (No. 1) and the tube wall is 0.01 inch. The annular clearances for the other two splitters (Nos. 2 and 3) are 0.02 inch and 0.03 inch, respectively. Setup No. 1 also includes the eight static pressure taps shown in Figure 1 for static pressure gradient determination.

The inner-zone and outer-zone flows—which will be referred to, respectively, as the main flow and the sample flow in the following discussion—leave the test section through concentric passageways (see Figure 2). The main flow is in the outer passage and acts as a steam-water jacket around the sample flow, to minimize heat loss from the sample. The main flow then goes to a steam drum and the sample goes to a mixer-type calorimeter, as shown in Figure 3. The sample is mixed with a measured rate of cold water which condenses any steam in the sample. The rate and enthalpy of the mixture and the increase in enthalpy of the cold water in going through the calorimeter, are sufficient to determine the sample rate and enthalpy. A slight correction is necessary to account for heat loss from the calorimeter itself.

The quantities that are measured in Setup No. 1 are:

	Symbol	Estimated Error Limits
• System pressure (at exit end of test section)	P	±10 psi
• Total flow rate (just ahead of test section inlet)	$\dot{W}$	±2%
• Inlet temperature	T_1	±5°F
• Power to test section	$\dot{Q}$	±1%
• Exit temperature	T_2	±½%*
• Cold water flow rate	$\dot{W}_C$	±2%
• Cold water temperature	T_C	±½%*
• Mixture (cold water plus sample) flow rate	$\dot{W}_{C+S}$	±2%
• Mixture temperature	T_{C+S}	±½%*
• Static pressure profile over the last eight feet ahead of the exit.	ΔP	±0.02 psi

Various values of inlet temperature and power are used in combination with the various splitters and points of power lead attachment, to determine the effect of mass rate, quality, and distance from the end of the heated length, on the sample flow in three different annular zones and on the static pressure gradient.

*Datum is taken as thermocouple reference junction temperature (150°F).

Figure 2. Setup No. 1

Figure 3. Schematic of Loop with Setup No. 1

2.2 SETUP NO. 1 CALIBRATION

2.2.1 Flow

Three different flows are measured in Setup No. 1. The orifice sizes available for each flow are:

<i>Flow</i>	<i>Orifice Diameter (in.)</i>
Test section inlet	0.500
Cold water at calorimeter inlet	0.082 0.147 0.261
Mixture at calorimeter exit	0.172 0.305 0.540

The calibration results for the cold water and mixture orifices are shown in Figures 4 and 5, respectively. Note that for orifice diameters 0.172 inch and larger, 85% of the data is within ½% of the ASME value¹. The ASME values for the discharge coefficient are therefore used for all the larger orifices, including the main loop orifice which measures the flow to the test section inlet. The coefficients for the 0.082-inch and the 0.147-inch orifice are taken, respectively, as 0.98 times and 0.99 times the ASME value. The error in flow measurement should not exceed 2% for any of the orifices.

2.2.2 Temperature

The two calorimeter thermocouples used in September 1969 to measure cold water inlet temperature T_C and mixture exit temperature T_{C+S} were checked using an ice bath and boiling water at one atmosphere. The average of seven readings resulted in 4.097 mv, or 179.9°F. When the calorimeter was reassembled and used a year later, two different thermocouples were used. These, plus the thermocouples used to measure test section exit temperature T_2 , were calibrated by installing them at the test section exit, the point where system pressure is measured. The loop was then operated under two-phase conditions and various known pressures. The steam table values for temperature corresponding to these pressures were taken as the correct values for temperature at the test section exit. The result of several checks indicated a maximum difference of less than ½% (of the Fahrenheit temperature) between standard thermocouple table values and steam table values.

The three thermocouples measuring inlet temperature T_1 —even though at least two of them generally agreed—gave values which were not consistent when compared with the exit thermocouples. The inlet temperature error is bounded by $\pm 5^\circ\text{F}$.

2.2.3 Heat Loss

Because of problems measuring the test section inlet temperature, no reasonable value of heat loss from the test section could be determined. Therefore, the heat loss was calculated using a measured value of the temperature T_V on the test vessel wall and a value of $h = 2 \text{ Btu/h-ft}^2\text{-}^\circ\text{F}$. The resulting value of heat loss is

$$\begin{aligned} q_{LT} &= hA (T_V - T_F) \\ &= 2 \times 26 (208 - 74) = 6970 \text{ Btu/h.} \end{aligned} \quad (1)$$

In setting conditions, the power is increased a corresponding amount, or if the heat flux is being held constant, the inlet subcooling is decreased a corresponding amount; thus,

$$\Delta h_s = \Delta h'_s - \frac{q_{LT}}{3600 \text{ W}} \quad (2)$$

Figure 4. Cold Water Orifice Coefficients

Figure 5. Mixture Orifice Coefficients

where $\Delta h'_s$ is the subcooling calculated for zero heat loss. Inasmuch as this correction results in a change in exit quality of less than ½ percentage point, no greater accuracy was deemed necessary in its determination.

Heat lost from the sample as it moves from the point where it separates from the main flow to the point where it leaves the calorimeter, is all referred to as the calorimeter heat loss. It is determined by measuring the temperature drop in a sample when hot single-phase conditions exist in the test section. Careful measurements made at one sample flow rate (room temperature 73.5°F) give

$$\begin{aligned} q_{LC} &= 3600 \dot{W}_{cp} (T_2 - T_3) \\ &= 3600 \times 0.074 \times 1 \times (475 - 472) = 745 \text{ Btu/h.} \end{aligned} \quad (3)$$

It is assumed that this loss is independent of sample flow rate, and depends only on the average temperature difference between the calorimeter and surroundings:

$$q_{LC} = \frac{745}{400} \left(\frac{T_2 + T_3}{2} - T_r \right) \quad (4)$$

In practice, it is found that this heat loss is negligible, compared with the total heat transfer rate in the calorimeter, so a constant value of 745 Btu/h has been used to correct the data, as reported in Section 3.

2.2.4 Single Phase Friction Factor

Single-phase adiabatic pressure drop data are listed in Table 1.

The friction factor f is plotted against the Reynolds number in Figure 6. The Blasius expression,

$$f = \frac{0.3164}{N_R^{0.25}} \quad (5)$$

and a modification of the Blasius,

$$f = \frac{0.34}{N_R^{0.25}} \quad (6)$$

are both superposed. The modified Blasius fits two of the five points exactly, and is a "best fit" to the remaining three.

Table 1
SINGLE-PHASE ADIABATIC PRESSURE DROP DATA

Run No.	$\dot{W}$ (lb/sec)	T (°F)	$\Delta P/\Delta z$ (lb/ft ³)	$\Delta P_f/\Delta z$ (lb/ft ³)	$f/10^{-2}$	$N_R/10^4$
1	1.730	77.5	82.05	43.00	2.14	6.5
2	2.179	83.0	68.30	63.62	1.99	8.8
3	1.073	78.0	82.05	17.29	2.23	4.0
4	1.020	539.0	61.76	16.15	1.62	33.8
5	0.729	470.0	57.18	6.68	1.51	21.5

Figure 6. Single-Phase Friction Factor

2.2.5 Isokinetic Setting

It has been shown^{2, 3} that as a consequence of the friction factor being given by the Blasius expression, equation (5), the velocity profile (in a circular tube) is given by

$$u^+ = 8.74 (y^+)^{1/7}, \quad (7)$$

where

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

$$y^+ = \frac{v^* y}{(\mu/\rho)},$$

$$v^* = \bar{u} \sqrt{f/8}.$$

This holds generally, except in the region next to the wall, where the velocity is more accurately described by the Von Karman expressions,³

$$u^+ = y^+, \quad 0 < y^+ < 5,$$

$$u^+ = 5 \ln y^+ - 3.05, \quad 5 < y^+ < 30, \text{ and} \quad (8)$$

$$u^+ = 2.5 \ln y^+ + 5.5, \quad y^+ > 30.$$

Equations (7) and (8) agree at $y^+ = 50.0$. Equation (8) is assumed to hold for all y^+ less than 50.0.

To obtain a true time-average measure of the flow in the region next to the wall of the tube, (outer zone, Setup No. 1), it is important to split the outer zone (or sample) flow from the inner zone (or main) flow without disturbing the tube velocity profile. This condition (isokinetic flow) is assumed to exist, as noted earlier, when the sample flow rate is adjusted so that the wall and centerline static pressures are equal at the section where the sample is being extracted (Figure 2).

For single-phase isokinetic flow, the sample fraction of the total flow $\dot{W}_s/\dot{W}$ may be predicted analytically, using the velocity information given by Equations (7) and (8). The sample fraction depends on the relative splitter clearance Δ/D and the tube Reynolds number. The calculated sample fraction may then be compared with the measured sample fraction obtained during the single-phase calibration runs for Setup No. 1.

The single-phase isokinetic sample data are listed in Table 2. The calculated sample fraction for each of the three splitters is presented in Figure 7, as a function (shown as a dashed line) of tube Reynolds number for the corresponding ratio of splitter clearance to tube diameter Δ/D . The measured values of the sample fraction from table 2 for each of the three splitters are superposed.

It is evident from Figure 7 that when the assumed conditions for isokinetic flow are established, the imaginary cylindrical surface separating sample flow from main flow just ahead of splitter no. 1 has a diameter smaller than the splitter's outside diameter, i.e., Δ/D for the imaginary cylinder is larger. The same is true in the case of splitter no. 2, but the difference between the splitter and the imaginary cylinder is less. In the case of splitter no. 3, there is essentially no difference between splitter and imaginary cylinder. The calculated curves based on $\Delta/D = 0.0214$ for splitter no. 1, $\Delta/D = 0.0329$ for splitter no. 2, and $\Delta/D = 0.0468$ for splitter no. 3, agree quite well with the single phase data except for a few questionable points. It has been assumed in the subsequent reduction of data that the effective diameters of the tube and three splitters and the corresponding effective values for Δ are:

	Diameter			Δ	Δ/D
	Design Value (inch)	Measured Value (inch)	Effective Value (inch)	Effective Value (inch)	
Tube i.d.	0.68	0.6834	0.6834	0	0
Splitter No. 1 o.d.	0.66	0.6596	0.6542	0.0146	0.0214
Splitter No. 2 o.d.	0.64	0.6407	0.6385	0.0225	0.0329
Splitter No. 3 o.d.	0.62	0.6204	0.6194	0.0320	0.0468

Table 2
SINGLE PHASE ISOKINETIC SAMPLE FLOW AND
TUBE REYNOLDS NUMBER

A. DATA TAKEN SEPT. 1969

Run No.	Splitter No.	W (lb/sec)	W_S (lb/sec)	W_S/W (lb/sec)	$N_R \times 10^{-4}$
1001	1 ↓	1.069	0.0411	0.0384	4.20
1002		1.282	0.0645	0.0503	5.30
1003		0.706	0.0320	0.0454	3.19
1004		0.603	0.0265	0.0440	2.11
1005		0.827	0.0370	0.0447	3.03
1006		1.005	0.0479	0.0476	3.68
1007		1.206	0.0587	0.0487	4.63
1008		1.075	0.0612	0.0569	19.20
1009		1.072	0.0462	0.0431	20.10
1010		1.073	0.0632	0.0589	29.80
1011		1.079	0.0363	0.0336	30.00
1012		1.083	0.1043	0.0963	30.10
3001	3 ↓	0.714	0.0927	0.1299	3.19
3002		1.070	0.1384	0.1294	4.81
3003		0.722	0.0943	0.1306	22.00
3004		1.079	0.1453	0.1346	33.40

Table 2 (Continued)
SINGLE PHASE ISOKINETIC SAMPLE FLOW AND
TUBE REYNOLDS NUMBER

B. DATA TAKEN SEPT. 1970

Run No.	Splitter No.	W (lb/sec)	W _S (lb/sec)	W _S /W (lb/sec)	N _R × 10 ⁻⁴
1029	1 ↓	0.359	0.0137	0.0382	1.28
1030		0.713	0.0270	0.0378	2.77
1031		0.712	0	0	2.62
1032		0.714	0.0414	0.0579	2.63
1033		1.071	0.0436	0.0408	4.25
1034		1.060	0.0289	0.0270	4.35
1035		1.070	0.0541	0.0506	4.42
1036		0.357	0.0107	0.0299	1.50
1037		0.362	0.0139	0.0385	1.75
1038		0.537	0.0236	0.0439	2.70
1039		0.709	0.0323	0.0455	3.57
1040		0.892	0.0425	0.0476	4.49
1041		1.065	0.0504	0.0474	5.43
1042		1.245	0.0605	0.0486	6.56
1043		1.159	0.0574	0.0495	6.02
1044		0.981	0.0474	0.0483	5.16
1045		0.806	0.0385	0.0477	4.27
1046		0.632	0.0287	0.0453	3.46
1047		0.457	0.0202	0.0442	2.49
2018	2 ↓	0.712	0.0659	0.0926	18.2
2019		1.071	0.0985	0.0919	28.8
2020		0.719	0.0657	0.0915	19.3

Figure 7. Ratio, Sample Flow Rate to Total Flow Rate under Single-Phase Conditions

2.2.6 Nonisokinetic Setting

Several runs were made with Setup No. 1, during which film samples were drawn off under nonisokinetic conditions. When the sampling is done isokinetically, the sample flow rate $\dot{W}_S$ is adjusted so that the static pressure P_W on the channel wall (same axial position as leading edge of splitter) is just equal to the static pressure P_C on the channel centerline. When the sampling is done nonisokinetically, P_W is different from P_C . Results for each of the three Splitters are listed in Table 3, and plotted as $P_W - P_C = \Delta P_{WC}$ versus $\dot{W}_S$ in Figures 8 and 9, single phase and two-phase respectively. These results show that the sample rate is not very sensitive to ΔP_{WC} , for either the single phase or two-phase runs. For example, ΔP_{WC} can be set to ± 0.002 psi. The corresponding variation in $\dot{W}_S$ is of the order of 1% or less. This is smaller than the error limits in the measurement of $\dot{W}_S$.

Referring to Table 3, the nonisokinetic sample quality for the two-phase runs shows some scatter but no consistent trend with ΔP_{WC} . With the exception of one run, the greatest scatter is less than three percentage points, which is of the same order as the scatter in the isokinetic data described in Section 4. No significance can be attached to the variation in sample quality for the nonisokinetic runs.

2.3 SETUP NO. 2

Under conditions of annular flow, the thickness of the liquid film* at the exit end of the tube can be measured by a conductivity probe. The probe may also be useful for flow regime determination when the flow is not annular.

The quantities that are measured in Setup No. 2 are:

	<i>Symbol</i>	<i>Estimated Error Limits</i>
• System pressure	P	± 10 psi
• Total flow rate	$\dot{W}$	$\pm 2\%$
• Inlet temperature	T_1	$\pm 5^\circ\text{F}$
• Power to test section	$\dot{Q}$	$\pm 1\%$
• Exit temperature	T_2	$\pm 1/2\%^\dagger$
• Conductivity probe conductance (versus time)		
• Conductivity probe position	y	± 0.001 inch

† Datum is taken as thermocouple reference junction temperature (150°F).

Various values of inlet temperature and power are used in combination with the various points of power lead attachment, to set the same conditions for which data were obtained in Setup No. 1. The effect on film thickness is then determined for mass rate, quality, and distance from the end of the heated length. The results may be correlated with the sample flow and pressure gradient measurements made with Setup No. 1.

2.3.1 Description of Conductivity Probe

The conductivity probe, as shown in Figure 10, consists of a 1/16-inch-diameter stainless steel conductor which is insulated from its surroundings by means of a Teflon tube that totally encases it, except for a small, sharp point on the inside end (projects into the channel), and a terminal on the other (outside) end. The Teflon tube, in turn, is housed inside a 1/8-inch-o.d. stainless steel tubular sheath which has a gland attached to its outside end. The gland provides a seal for the conductor and Teflon tube insulator. The inside end of the sheath was reduced in diameter to 3/32 inch to minimize flow disturbance. The 1/8-inch-o.d. portion of the sheath passes through a water-cooled O-ring gland in the probe fixture. A micrometer head, with its dial graduated in one ten-thousandths of an inch, is used to traverse the probe in or out, while the system pressure provides sufficient force (approximately 12 pounds) on the probe to maintain firm contact with the micrometer head. The threaded end of the probe fixture facilitates the attachment of the conductivity probe to the exit end of the circular tube test section.

*The existence of a continuous liquid film is a generally accepted concept of the annular and annular-dispersed flow regimes which is often used in models of these regimes. However, the liquid film is known to carry entrained vapor, and the interface between liquid and vapor is often very poorly defined. The idea of a film may be an oversimplification.

Table 3
NONISOKINETIC SAMPLE FLOW
A. DATA TAKEN SEPT. 1969
Single Phase

Run No.	Splitter No.	Δ/D	L_u (ft)	$\dot{W}$ (lb/sec)	$\dot{W}_S$ (lb/sec)	$\dot{W}_S/\dot{W}$ (lb/sec)	$N_R \times 10^{-4}$	$P_W - P_C$ (psi)
3001.A	3	0.0468	4	0.714	0.1164	0.1640	3.19	-0.060
3001*				0.714	0.0927	0.1299	3.19	0
3001.B				0.714	0.0492	0.0689	3.19	+0.060
3002.A				1.070	0.1590	0.1483	4.81	-0.060
3002*				1.070	0.1384	0.1294	4.81	0
3002.B				1.070	0.1237	0.1153	4.81	+0.060
3003.A				0.722	0.1110	0.1540	22.0	-0.060
3003*				0.722	0.0943	0.1306	22.0	0
3003.B				0.722	0.0684	0.0949	22.0	+0.060
3004.A	3	0.0468	4	1.079	0.1597	0.1477	33.4	-0.060
3004*				1.079	0.1453	0.1346	33.4	0
3004.B				1.079	0.1311	0.1217	33.4	+0.060

Two Phase

Run No.	Splitter No.	Δ/D	L_u (ft)	$\bar{G}/10^6$ (lb/h-ft ²)	$\phi/10^6$ (Btu/h-ft ²)	$\bar{X}$	$\dot{W}_S$ (lb/sec)	$\dot{W}_S/\dot{W}$ (lb/sec)	X_S	$P_W - P_C$ (psi)
1015.A	1	0.0214	8	1.026	0.313	0.200	0.0799	0.1112	0.0079	-0.0128
1015**				1.026	0.313	0.200	0.0791	0.1101	0.0097	0
1015.B				1.026	0.313	0.200	0.0727	0.1012	0.0256	+0.048
1016.A				1.024	0.253	0.099	0.0716	0.0998	-0.0122	-0.0468
1016**				1.024	0.253	0.099	0.0635	0.0885	0.0116	0
1016.B	1	0.0214	8	1.024	0.253	0.099	0.0616	0.0859	0.0180	+0.042

B. DATA TAKEN SEPT. 1970
Single Phase

Run No.	Splitter No.	Δ/D	L_u (ft)	$\dot{W}$ (lb/sec)	$\dot{W}_S$ (lb/sec)	$\dot{W}_S/\dot{W}$ (lb/sec)	$N_R \times 10^{-2}$	$P_W - P_C$ (psi)
2019.A	2	0.0329	8	1.068	0.1069	0.1001	28.8	-0.060
2019*				1.071	0.0985	0.0919	28.8	0
2019.B				1.067	0.0862	0.0808	28.9	+0.060
2020.A				0.719	0.0774	0.1076	19.1	-0.060
2020*				0.719	0.0657	0.0915	19.3	0
2020.B	2	0.0329	8	0.717	0.0445	0.0621	19.2	+0.060

Table 3 (Continued)

Two Phase

Run No.	Splitter No.	Δ/D	L_u (ft)	$\bar{G}/10^6$ (lb/h-ft ²)	$\phi/10^6$ (Btu/h-ft ²)	$\bar{X}$	$\dot{W}_S$ (lb/sec)	$\dot{W}_S/\dot{W}$ (lb/sec)	x_S	$P_W - P_C$ (psi)
1063.A	1	0.0214	8	1.003	0.190	0.1976	0.0830	0.1171	0.0081	-0.060
1063**				1.003	0.190	0.1978	0.0785	0.1108	0.0058	0
1063.B				1.002	0.190	0.2002	0.0742	0.1048	0.0079	+0.064
1064.A				1.006	0.308	0.4055	0.0718	0.1010	0.0676	-0.060
1064**				1.008	0.308	0.4026	0.0689	0.0968	0.0569	0
1064.B				1.006	0.309	0.4056	0.0668	0.0940	0.0486	+0.064
1066.A				1.016	0.252	0.2059	0.0614	0.0854	0.0330	-0.064
1066**				1.010	0.253	0.2035	0.0555	0.0773	0.0314	0
1066.B			8	1.021	0.250	0.1970	0.0491	0.0681	0.0247	+0.060
1080.A			0	0.506	0.502	0.1425	0.0374	0.1047	0.0567	-0.060
1080**			0	0.505	0.502	0.1517	0.0298	0.0835	0.0479	0
1080.B			0	0.503	0.505	0.1465	0.0118	0.0332	0.1564	+0.060
1092.A			8	1.525	0.197	0.1471	0.0952	0.0883	0.0150	-0.060
1092**				1.525	0.196	0.1438	0.0917	0.0917	0.0118	0
1092.B				1.525	0.195	0.1418	0.0888	0.0824	0.0410	+0.060
1093.A				1.504	0.244	0.2040	0.0981	0.0923	0.0141	-0.060
1093**				1.536	0.243	0.1956	0.0955	0.0880	0.0150	0
1093.B				1.526	0.245	0.1972	0.0918	0.0851	0.0092	+0.060
1098.A				0.511	0.099	0.1516	0.0389	0.1078	0.0071	-0.060
1098**				0.511	0.102	0.1641	0.0352	0.0975	-0.0118	0
1098.B	1	0.0214		0.511	0.105	0.1750	0.0250	0.0693	-0.0069	+0.060
2023.A	2	0.0329		1.023	0.089	0.0564	0.1036	0.1433	0.0030	-0.060
2023**				1.024	0.089	0.0535	0.0944	0.1305	0.0022	0
2023.B				1.022	0.089	0.0583	0.0798	0.1105	0.0049	+0.060
2026.A				1.014	0.147	0.1579	0.1296	0.1808	0.0107	-0.060
2026**				1.014	0.147	0.1552	0.1237	0.1727	0.0085	0
2026.B				1.012	0.146	0.1575	0.1191	0.1666	0.0088	+0.060
2029.A				1.521	0.233	0.1938	0.1714	0.1595	0.0265	-0.112
2029**				1.517	0.233	0.1951	0.1677	0.1564	0.0230	0
2029.B				1.519	0.233	0.1960	0.1635	0.1523	0.0237	+0.079
2034.A				1.019	0.166	0.1850	0.1341	0.1862	0.0153	-0.080
2034**				1.018	0.168	0.1878	0.1299	0.1805	0.0102	0
2034.B	2	0.0329	8	1.018	0.166	0.1870	0.1227	0.1705	0.0127	+0.071

*These runs are isokinetic and are also listed in Table 2.

**These runs are isokinetic and are also listed in Table 4.

Figure 8. Single-Phase Nonisokinetic Sample Flow

Figure 9. Two-Phase Nonisokinetic Sample Flow

Figure 10. Conductivity Probe

2.3.2 Principle of Operation

The probe method has been developed and used by McManus,⁴ Hewitt, et al.,⁵ and Bergles, et al.⁶ The conductivity probe is inserted through the wall of the circular tube so that it can traverse normally to the opposite wall. When fully inserted, it must make electrical contact with the opposite wall; hence, that wall must be an electrical conductor. As the probe is withdrawn, it first loses direct contact with the wall, but maintains contact via a continuous bridge of liquid in the film. As the probe is further withdrawn, the bridge of liquid becomes discontinuous (as though the probe has encountered the troughs of occasional passing waves), and finally—provided the flow regime is truly annular—there is no bridge at all (as though the probe has cleared the crests of all passing waves). Following McManus,⁴ the average thickness of the film is taken as the distance from the wall at which the probe loses contact with the liquid bridge 50% of the time.

2.4 SETUP NO. 2 CALIBRATION

The remarks concerning flow and temperature calibration and test section heat loss for Setup No. 1, apply also to Setup No. 2. The only instrument unique to Setup No. 2 is the conductivity probe.

2.4.1 Calibration of Conductivity Probe

An image-retaining oscilloscope (1 megohm pure resistive input impedance), connected in series with the conductivity probe and a battery as shown in Figure 11, was adjusted to yield an output signal of 6 volts dc when the probe was in contact with the wall, and a zero output voltage with open circuit.

After the test loop had been adjusted to provide single-phase flow at the test section exit with the water temperature at or near 545°F, the conductivity probe was traversed from the wall toward the center of the tube. Once the probe was out of contact with the wall, the output signal remained nearly constant at approximately 5 volts for all probe positions. The test loop conditions were then adjusted to provide two-phase, high-quality, annular flow at the exit end of the test section. The conductivity probe was traversed to the center of the tube, where the tip of the probe would be in the vapor phase. The output signal at this position was approximately zero.

The foregoing measurements give the upper and lower limits for the output signal where the probe "sees" only liquid phase and only vapor phase, respectively, and thus provide a guide in the determination of liquid film thickness.

Figure 11. Conductivity Probe Circuit

2.4.2 Film Thickness Determination

When the predetermined steady-state test section conditions became established, the conductivity probe was traversed from the center of the tube toward the opposite wall, while observing the output signal on the image-retaining oscilloscope. The image was retained for several sweeps, then erased, the probe was moved a little farther, and the image again was retained for several sweeps. The oscilloscope beam intensity was adjusted to a low value so that when several traces were superposed, the resulting image was very faint, except where successive traces tended to lie on top of each other. Density of the image then became a measure of the time the probe was "seeing" all liquid or all vapor, or something in between. The probe was finally traversed to a position where the image density (see Figure 12) appeared to be equally distributed between the upper and lower limits of the output signal, as established in the probe calibration. This was then considered to be the position of the probe at which the probe is out of contact with the liquid bridge 50% of the time. Moving the probe in either direction from the above position results in an unequal distribution of image density on the oscilloscope screen, as shown in Figure 12.

The micrometer head reading was recorded for the foregoing probe position. The probe was then traversed toward the wall until contact with the wall was achieved, and the micrometer head reading was again recorded. The liquid film thickness was then taken as the difference between the two micrometer head readings for the two probe positions.

This procedure was repeated at least twice for every run. The second probe traverse would usually proceed from the wall toward the tube center, the third probe traverse from the tube center toward the wall, and so on. The average liquid film thickness as obtained from the three or more traverses was then recorded as the measured liquid film thickness.

$Y = 0.010$ (TOO CLOSE TO WALL)

$Y = 0.035$ (PROBE AT MEAN POSITION OF INTERFACE)

$Y = 0.100$ (TOO FAR FROM WALL)

Figure 12. Typical Oscilloscope Photos Used to Judge When the Probe Was "Seeing" a Continuous Liquid Film Bridge to the Wall 50% of the Time (Run No. 40.5).

3. REDUCTION OF DATA

3.1 FLOW AND QUALITY

The ratio of mass rate to orifice coefficient is given by

$$\frac{\dot{W}}{K_O} = \frac{\rho_0}{\rho_{75}} \rho_{75} A_0 \sqrt{\frac{2g}{12}} \sqrt{\Delta h_0} \quad (9)$$

The term ρ_0/ρ_{75} can be expressed as a fourth-degree polynomial in T_0 with two pressure-dependent coefficients.

$$\begin{aligned} \frac{\rho_0}{\rho_{75}} = & 0.86325 \left[1 + \frac{2.65}{10^6} \left\{ P - 1000 \right\} \right] \left[1 - \frac{0.7584}{10^3} \left\{ T_0 - 400 \right\} - \right. \\ & \frac{1.0429}{10^6} \left\{ T_0 - 400 \right\}^2 - \frac{1.9230}{10^9} \left\{ T_0 - 400 \right\}^3 - \frac{3.948}{10^{12}} \left\{ T_0 - 400 \right\}^4 + \\ & \left. \frac{1}{10^5} \left\{ P - 1000 \right\} \left\{ \frac{2.4909}{10^3} \left\{ T_0 - 400 \right\} + \frac{4.7606}{10^6} \left\{ T_0 - 400 \right\}^2 \right\} \right]. \end{aligned} \quad (10)$$

Values given by Equation (10) agree with values for compressed water given in Reference 5, to within 0.1% over the entire range of test conditions. The density of water at 75°F is a linear function of pressure,

$$\rho_{75} = 62.25 \left[1 + \frac{3.11}{10^6} P \right]. \quad (11)$$

The orifice area changes slightly with temperature. Assuming the orifice plate and flange to be at the same temperature as the liquid,

$$A_0 = \frac{\pi}{4} D_{0.75}^2 \left[1 + 2K \left\{ T_0 - 75 \right\} \right]. \quad (12)$$

where K is the coefficient of expansion for Type-304 stainless steel.

The head difference across the orifice is given by

$$\Delta h_0 = \frac{\rho_r/\rho_{75}}{\rho_0/\rho_{75}} \left\{ \frac{\rho_{\text{man}}}{\rho_r} - 1 \right\} \Delta h'_0 - \left\{ \frac{\rho_r/\rho_{75}}{\rho_0/\rho_{75}} - 1 \right\} \Delta z_0. \quad (13)$$

$\frac{\rho_r}{\rho_{75}}$ is given by Equation 10.

The term Δz_0 is simply the difference in elevation between the upstream and downstream orifice taps. Because the orifice for all the data reported here is in a horizontal run, this term is zero. The term $\Delta h'_0$ is the orifice manometer deflection. The ratio of manometer fluid density to water density is essentially independent of pressure, and depends primarily on temperature,

$$\frac{\rho_{\text{man}}}{\rho_r} = K_1 + K_2 (T_r - 75) + K_3 (T_r - 75)^2. \quad (14)$$

K_1 , K_2 , and K_3 depend on the particular manometer fluid used. The values for two different fluids are given in the following table.

Manometer Fluid	K ₁	K ₂	K ₃
Meriam No. D-8325 (blue)	1.7419	-0.1812/10 ³	+0.382/10 ⁵
Meriam No. D-2883 (red)	2.9613	-0.2787/10 ³	+0.163/10 ⁵

The ratio of orifice Reynolds number to orifice coefficient is given by

$$\frac{N_{R_0}}{K_0} = \frac{4}{\pi D_0 \mu_0} \frac{\dot{W}}{K_0} \quad (15)$$

$\frac{\dot{W}}{K_0}$ is given by Equation (9).

The term μ_0 is a function of temperature which is represented to sufficient accuracy ($\pm 2\%$) over the range of test conditions by the following polynomial:

$$\mu_0 = -\frac{0.046}{10^4} + \frac{3.435}{10^2} T_0^{-1} + 1.810 T_0^{-2} - 66.5 T_0^{-3} \quad (16)$$

The term K_0 is a function of $\frac{N_{R_0}}{K_0}$, which is represented to sufficient accuracy ($\pm 0.1\%$) by

$$K_0 = C_0 + C_1 \left(\frac{N_{R_0}}{K_0} \right)^{-1} + C_2 \left(\frac{N_{R_0}}{K_0} \right)^{-2} + C_3 \left(\frac{N_{R_0}}{K_0} \right)^{-3} \quad (17)$$

The terms C_0 , C_1 , C_2 , and C_3 depend upon the particular orifice. For the main flow data reported here, a 1/2-inch orifice was used, for which the constants are:

$$\begin{aligned} C_0 &= 0.5952, \\ C_1 &= 141.766, \\ C_2 &= -60693.8, \text{ and} \\ C_3 &= 0. \end{aligned}$$

The mass rate is given by the product of the left-hand sides of Equations (9) and (17).

$$\dot{W} = \left(\frac{\dot{W}}{K_0} \right) K_0 \quad (18)$$

The mass flux is

$$\bar{G} = \left(\frac{3600}{A} \right) \dot{W} \quad (19)$$

The quality is determined from an energy balance,

$$X = \frac{1}{h_{fg}} \left[\frac{3413 \cdot \text{kilowatts} - q_{LT}}{3600 \dot{W}} - \Delta h_s \right] \quad (20)$$

The test section heat loss q_{LT} is determined from calculations as noted in the previous section.

3.2 PRESSURE DROP

The pressure drop between the reference pressure tap and any other tap along the test channel is given by

$$\Delta P = P_{ref} - P_i = \left[z_i - z_{ref} + \left\{ \frac{\rho_{man}}{\rho_r} - 1 \right\} \Delta h' \right] \frac{\rho_r}{\rho_{75}} \frac{\rho_{75}}{1728} \quad (21)$$

The expression for ρ_{man}/ρ_r is given by Equation (14). The manometer fluid may be different than that used for flow measurement, in which case a different set of values for K_1 , K_2 , and K_3 may be used.

4. RESULTS

4.1 SAMPLE FLOW RATE (SETUP NO. 1)

The isokinetic sample flow rates for the three different splitters were measured at (actually, approximately 3/16 inch past) the end of the heated length (unheated length $L_u = 0$), at two feet past the end of the heated length ($L_u = 2$), and at eight feet past the end of the heated length ($L_u = 8$). A few points were obtained for splitter number 1 with two-phase conditions at inlet, which corresponds to 23.8 feet of unheated length ($L_u = 23.8$). All isokinetic sample flow results are listed in Table 4, and are plotted in Figures 13 through 18 as the ratio of sample flow rate to total channel flow rate ($\dot{W}_s/\dot{W}$) versus average channel quality ($\bar{X}$). Each of these figures is for a particular value of average channel mass velocity ($\bar{G}$), and, except for Figures 13 and 16, a particular value of L_u . Smooth curves have been fitted to the data points for each splitter. The uncertainty interval has been indicated for certain typical data points in accordance with the error analysis given in Appendix A. These intervals show that the smooth curves are valid representations of the data. The curves have been ordered in different ways and replotted in Figures 19, 20, and 21 to show the effect of L_u at $\bar{G} = 1 \times 10^6$ lb/h-ft² (Figure 19), and the effect of $\bar{G}$ at $L_u = 0$ (Figure 20) and $L_u = 8$ (Figure 21).

Consider first Figure 13 ($\bar{G} = 0.5 \times 10^6$ lb/h-ft², $L_u = 0$ and $L_u = 8$). $L_u = 0$ corresponds to boiling conditions i.e., single component two-phase flow with heat transfer. $L_u = 8$ corresponds to developed (possibly fully developed) adiabatic two-phase flow conditions. Figure 13 shows that the flow rate in the 0.0146 inch thick zone next to the wall (splitter number 1) under heat transfer conditions ($L_u = 0$) is greater than the flow rate in the same zone under single phase conditions. The flow rate in this zone increases with increasing $\bar{X}$, and for $\bar{X} > 0.30$ is more than 50% greater than the flow rate under single phase conditions. The flow rate under developed adiabatic conditions ($L_u = 8$), in turn, is even greater than the flow rate under heat transfer conditions, by about 50%. For $\bar{X} > 0.25$ it is more than twice the flow rate under single phase conditions. It is evident from Figure 13 that significant radial transfer of mass (as much as 5% of the total mass flowing) takes place from the interior region to the zone next to the wall as the total flow moves from the end of the heated length (heat flux $\phi \approx 0.5 \times 10^6$ Btu/h-ft²) to the end of the unheated length.

Figure 14 ($\bar{G} = 1.0 \times 10^6$, $L_u = 0$) permits comparison of the sample flow rate for all three splitters under two-phase conditions, with their respective single phase values and with each other. The sample flow rate for splitter numbers 1 and 2 at low and slightly negative qualities is less than the single phase sample flow rate. It is evident that subcooled voids are present close to the wall at near zero quality. On the other hand, the sample flow rate for splitter numbers 1 and 2 at qualities greater than 0.06 and 0.04, respectively, and for splitter number 3 at all qualities, is greater than the single phase sample flow rate. The liquid phase tends to concentrate close to the wall under these two-phase conditions. The strong inflection in the curve through splitter number 3 points at the low quality end is due to the position of the lowest quality point, and indicates much higher sample flow under subcooled conditions than the single phase value. This lowest quality point is suspect. A manometer might have been read incorrectly, for example. The other points are consistent, and for splitter number 1 the points taken September 1970 are in good agreement with the points taken September 1969.

Table 4
TWO-PHASE SAMPLE FLOW AND QUALITY FOR SPLITTERS NOS. 1, 2, AND 3
A. DATA TAKEN SEPT. 1969

Run No.	Splitter No.	Δ/D	L_u (ft ²)	$\bar{G}/10^6$ (lb/h-ft ²)	$\phi/10^6$ (Btu/h-ft ²)	$\bar{X}$	$\dot{W}_s/\dot{W}$ (lb/sec)	X_s
1013	1	0.0214	8	1.540	0.357	0.190	0.0959	0.0022
1014			↓	1.031	0.341	0.251	0.1087	0.0197
1015			↓	1.026	0.313	0.200	0.1101	0.0097
1016			↓	1.024	0.253	0.099	0.0885	0.0116
1017			0	1.543	0.551	0.055	0.0513	0.0231
1018			↓	1.540	0.554	0.111	0.0615	0.0310
1019			↓	1.525	0.557	0.221	0.0492	0.1023
1020			↓	1.033	0.556	0.278	0.0680	0.0611
1021			↓	1.021	0.557	0.218	0.0821	0.0447
1022			↓	1.034	0.557	0.105	0.0701	0.0421
1023			↓	1.020	0.558	0.080	0.0597	0.0379
1024			↓	1.022	0.557	0.027	0.0504	0.0392
1025			↓	1.013	0.558	-0.026	0.0476	0.0165
1026			2	1.018	0.558	0.051	0.0731	0.0183
1027			↓	1.025	0.548	0.097	0.0875	0.0152
1028			↓	1.027	0.551	0.182	0.1054	0.0096
2001	2	0.0329	2	1.020	0.554	0.201	0.1942	0.0085
2002			↓	1.020	0.555	0.097	0.1669	0.0114
2003			↓	1.024	0.561	0.097	0.1636	0.0082
2004			↓	1.037	0.556	0.030	0.1217	0.0099
2005			0	1.027	0.558	0.291	0.1128	0.1115
2006			↓	1.025	0.558	0.190	0.1369	0.0369
2007			↓	1.025	0.559	0.089	0.1147	0.0297
2008			↓	1.021	0.552	0.064	0.1008	0.0369
2009			↓	1.042	0.552	-0.009	0.0864	0.0166
2010			↓	1.023	0.557	-0.085	0.0934	-0.0424
2011			↓	1.523	0.554	0.205	0.0949	0.1099
2012			↓	1.532	0.553	0.087	0.1014	0.0322
2013			↓	1.542	0.556	0.056	0.0924	0.0299
2014			8	1.044	0.149	0.051	0.1376	0.0091
2015			↓	1.031	0.180	0.095	0.1612	0.0123
2016			↓	1.043	0.258	0.177	0.1796	0.0195
2017			↓	1.045	0.337	0.291	0.1712	0.0498

Table 4 (Continued)

Run No.	Splitter No.	Δ/D	L_u (ft ²)	$\bar{G}/10^6$ (lb/h-ft ²)	$\phi/10^6$ (Btu/h-ft ²)	$\bar{X}$	$\dot{W}_s/\dot{W}$ (lb/sec)	X_s
3005	3	0.0468	8	1.022	0.369	0.048	0.1999	0.0133
3006				1.028	0.370	0.047	0.2084	0.0095
3007				1.025	0.283	-0.013	0.1416	-0.0060
3008				1.028	0.271	0.185	0.2538	0.0320
3009				1.033	0.340	0.288	0.2164	0.0963
3010				1.024	0.218	0.098	0.2344	0.0156
3011				1.535	0.224	0.043	0.1920	0.0121
3012				1.540	0.271	0.082	0.2057	0.0120
3013				1.542	0.357	0.170	0.2115	0.0397
3014			0	1.022	0.573	0.331	0.1456	0.2061
3015				1.024	0.574	0.223	0.1858	0.0787
3016				1.022	0.562	0.113	0.1969	0.0378
3017				1.024	0.565	0.065	0.1760	0.0204
3018				1.026	0.563	0.015	0.1480	0.0192
3019				1.024	0.567	-0.044	0.1783	-0.0619
3020				1.532	0.563	0.213	0.1406	0.1334
3021				1.538	0.571	0.104	0.1660	0.0436
3022				1.545	0.570	0.047	0.1454	0.0264
3023			2	1.020	0.569	0.206	0.2826	0.0187
3024				1.004	0.567	0.125	0.2586	0.0024
3025				1.024	0.554	0.037	0.2018	0.0051

Table 4 (Continued)

B. DATA TAKEN SEPT. 1970

Run No.	Splitter No.	Δ/D	Lu	$\bar{G}/10^6$ (lb/hr-ft ²)	$\phi/10^6$ (Btu/hr-ft ²)	$\bar{X}$	$\dot{W}_s/\dot{W}$	X_s
1048	1	0.0214	23.8'	1.015	0	0.278	0.0851	0.0026
1049				1.019	0	0.399	0.1010	0.0139
1050				1.016	0	0.493	0.0957	0.0439
1051				1.011	0	0.284	0.0842	0.0110
1052			▼	1.016	0	0.282	0.0863	0.0112
1053			8'	1.020	0.203	0.219	0.1055	0.0099
1054				1.013	0.250	0.311	0.0953	0.0171
1055				1.016	0.288	0.370	0.1062	0.0460
1056				1.012	0.309	0.3887	0.0991	0.0417
1057				1.022	0.250	0.2839	0.1042	0.0046
1058				1.008	0.250	0.2994	0.1127	0.0171
1059				1.028	0.249	0.2916	0.1120	0.0149
1060				1.026	0.250	0.2954	0.1112	0.0398
1061				1.003	0.308	0.4061	0.0977	0.0557
1062				1.017	0.191	0.2011	0.1108	0.0098
1063				1.003	0.190	0.1978	0.1108	0.0058
1064				1.008	0.308	0.4026	0.0968	0.0569
1065				1.025	0.250	0.2971	0.0726	0.0496
1066				1.016	0.253	0.2035	0.0773	0.0314
1067			▼	1.016	0.191	0.1957	0.0890	0.0056
1068			0	1.025	0.500	0.3177	0.0695	0.0546
1069				1.017	0.497	0.2762	0.0821	0.0266
1070				1.002	0.500	0.2626	0.0818	0.0322
1071				1.021	0.496	0.2760	0.0803	0.0389
1072				1.014	0.499	0.2099	0.0869	0.0214
1073				1.013	0.497	0.1321	0.0701	0.0315
1074				1.524	0.466	0.1903	0.0645	0.0355
1075				1.524	0.496	0.2119	0.0603	0.0466
1076				1.532	0.502	0.1973	0.0652	0.0426
1077				1.526	0.502	0.2010	0.0629	0.0488
1078				1.538	0.501	0.1445	0.0677	0.0317
1079				0.509	0.501	0.4044	0.0886	0.0425
1080				0.505	0.502	0.1517	0.0835	0.0479
1081				0.505	0.501	0.2422	0.0848	0.0501
1082				0.501	0.505	0.3550	0.0948	0.0626
1083				0.509	0.508	0.4790	0.0949	0.0736
1084				0.508	0.303	0.1684	0.0699	0.0465
1085			▼	1.008	0.306	0.1384	0.0753	0.0181
1086			2'	1.022	0.518	0.2207	0.1058	-0.0029
1087			▼	1.026	0.509	0.1484	0.0937	-0.0028

Table 4 (Continued)

Run No.	Splitter No.	Δ/D	Lu	$G/10^6$ (lb/hr-ft ²)	$\phi/10^6$ (Btu/hr-ft ²)	X	$\dot{W}_s/\dot{W}$	X_s
1088	1	0.0214	8	1.010	0.132	0.1091	0.0746	-0.0108
1089				1.021	0.163	0.1656	0.0939	0.0128
1090				1.030	0.216	0.2507	0.1058	0.0123
1091				1.520	0.158	0.1041	0.0794	0.0080
1092				1.525	0.196	0.1438	0.0917	0.0118
1093				1.536	0.243	0.1956	0.0880	0.0150
1094				1.524	0.285	0.2472	0.0864	0.0217
1095				1.531	0.339	0.3014	0.0765	0.0445
1096				1.517	0.342	0.3102	0.0748	0.0556
1097				0.508	0.091	0.1428	0.1038	0.0202
1098				0.511	0.102	0.1641	0.0975	-0.0118
1099				0.519	0.125	0.2356	0.1269	-0.0014
1100				0.520	0.143	0.2893	0.1267	0.0296
1101				0.519	0.172	0.3889	0.1527	0.0195
1102				0.515	0.204	0.5008	0.1380	0.0331
2021	2	0.0329	8'	1.019	0.060	0.0090	0.0965	0.0047
2022				1.016	0.072	0.0242	0.1144	-0.0016
2023				1.024	0.089	0.0535	0.1305	0.0022
2024				1.019	0.102	0.0809	0.1449	0.0051
2025				1.015	0.115	0.0991	0.1568	-0.0002
2026				1.014	0.147	0.1552	0.1727	0.0085
2027				1.533	0.148	0.0991	0.1435	0.0097
2028				1.530	0.191	0.1488	0.1645	0.0197
2029				1.517	0.233	0.1951	0.1564	0.0230
2030				1.529	0.284	0.0721	0.1420	0.0502
2031				1.534	0.333	0.3037	0.1201	0.1038
2032				1.025	0.116	0.1036	0.1537	0.0089
2033				1.012	0.146	0.1579	0.1732	0.0161
2034				1.018	0.168	0.1878	0.1805	0.0102
2035				1.025	0.202	0.2454	0.1807	0.0268
2036				1.028	0.229	0.2872	0.1739	0.0312
2037				1.017	0.292	0.3978	0.1347	0.1258
2038				0.507	0.089	0.1414	0.1778	0.0015
2039			2'	1.024	0.501	0.1648	0.1863	0.0036
2040				1.020	0.508	0.1368	0.1703	0.0041

Figure 13. Ratio, Sample Flow Rate to Total Flow Rate versus Average Channel Quality,
 $G = 0.5 \times 10^6 \text{ lb/h-ft}^2$, $L_u = 0$ and 8 ft .

Figure 14. Ratio, Sample Flow Rate to Total Flow Rate versus Average Channel Quality,
 $G = 1.0 \times 10^6 \text{ lb/h-ft}^2$, $L_u = 0$.

Figure 15. Ratio, Sample Flow Rate to Total Flow Rate versus Average Channel Quality,
 $G = 1.0 \times 10^6 \text{ lb/h-ft}^2$, $L_u = 2 \text{ ft}$.

Figure 16. Ratio, Sample Flow Rate to Total Flow Rate versus Average Channel Quality,
 $G = 1.0 \times 10^6 \text{ lb/h-ft}^2$, $L_u = 8 \text{ ft}$ and 23.8 ft .

Figure 17. Ratio, Sample Flow Rate to Total Flow Rate versus Average Channel Quality,
 $G = 1.5 \times 10^6 \text{ lb/h-ft}^2$, $L_u = 0$.

Figure 18. Ratio, Sample Flow Rate to Total Flow Rate versus Average Channel Quality,
 $G = 1.5 \times 10^6 \text{ lb/h-ft}^2$, $L_u = 8 \text{ ft}$.

Figure 19. Ratio, Sample Flow Rate to Total Flow Rate versus Average Channel Quality,
 $G = 1.0 \times 10^6$ lb/h-ft², Various L_u

Figure 20. Ratio, Sample Flow Rate to Total Flow Rate versus Average Channel Quality, $L_u = 0$, Various G .

Figure 21. Ratio, Sample Flow Rate to Total Flow Rate versus Average Channel Quality, $L_u = 8 \text{ ft}$, Various G .

Consider Figure 15 ($\bar{G} = 1.0 \times 10^6$, $L_U = 2$). $L_U = 2$ corresponds to developing (possibly nearly fully developed) adiabatic two-phase flow conditions. Figure 15 permits the same comparison as Figure 14. The sample flow rate for all three splitters is greater than their respective single phase values. This is because the liquid phase tends to concentrate close to the wall as already noted. The points for each splitter are consistent, and the points taken September 1970 are in good agreement with the points taken September 1969.

Consider Figure 16 ($\bar{G} = 1.0 \times 10^6$, $L_U = 8$ and $L_U = 23.8$). $L_U = 8$ corresponds to developed flow as noted before, and $L_U = 23.8$ is presumed to be fully developed flow. The first data taken on September 1970 were the data shown here for splitter number 1, $L_U = 23.8$, then $L_U = 8$. The points show unexpected scatter, which may be associated with the fact that these were the first runs of this type attempted for several months. The uncertainty intervals should perhaps be wider to account for the greater possibility of operator error. Because of the pressure of time, only five points were obtained for $L_U = 23.8$. These points are in at least fair agreement with the $L_U = 8$ points obtained subsequently. This is evidence that the two phase flow at $L_U = 8$ is essentially fully developed.

Continuing with Figure 16, the sample flow rate for all three splitters is again greater than their respective single phase values. The points for each splitter are consistent (except for the splitter number 1 scatter noted above), and the points taken September 1970 are in good agreement with the points taken September 1969. The smooth curves fitted to the points have been extended to intersect the single phase lines at zero quality. It is interesting to note that the two-phase lines do not "fair in" to their respective single phase lines, but rather intersect them at definite angles. This is in contrast to Figure 14 where fairing in is evidence, particularly for splitter numbers 1 and 2.

Consider Figure 17 ($\bar{G} = 1.5 \times 10^6$, $L_U = 0$). This is for the same condition as Figure 14 except that $\bar{G}$ is 50% greater. Data were not obtained at as low qualities as for Figure 14, but the trend of the Figure 17 data suggest that at low and slightly negative qualities the sample flow rate is less than the single phase sample flow rate, for all three splitters. This was noted in Figure 14 for splitter numbers 1 and 2. Again, it is evident that subcooled voids are present close to the wall at near zero quality.

Consider Figure 18 ($\bar{G} = 1.5 \times 10^6$, $L_U = 8$). The sample flow rate for all three splitters is greater than their respective single phase values, the same as noted in Figures 15 and 16. The points for each splitter are consistent, and the points taken September 1970 are in good agreement with the points taken September 1969. The smooth curves fitted to the points have been so drawn that if extended they would intersect the single phase limits at zero quality.

All of the isokinetic sample flow data for all three splitters have been plotted in the foregoing Figures 13 through 18. To facilitate further discussion, certain of the smooth curves have been ordered in certain ways and replotted, as noted earlier. Figure 19, for example, shows the effect of distance from the end of the heated length L_U on the sample flow rate for all three splitters, at the one average channel mass velocity $\bar{G} = 1.0 \times 10^6$ lb/h-ft². Referring to Figure 19, the sample flow rate at $L_U = 2$, and $\bar{X} \leq 0.15$ shows for splitter numbers 2 and 3 a slight tendency to be higher than, but for all three splitters is essentially the same as, the sample flow rate at $L_U = 8$. It is evident that the two-phase flow for $\bar{X} \leq 0.15$ is essentially fully developed in the first two feet. Significant radial transfer of mass takes place from the interior region to the zone next to the wall in the first two feet past the end of the heated length, sufficient to establish the conditions of fully developed flow.

There is a question whether the flow is fully developed at $L_U = 2$ for higher qualities.

Figure 20 shows the effect of $\bar{G}$ in the sample flow rate for all three splitters at $L_U = 0$. At low values of $\bar{X}$ ($\bar{X}$ less than 0.12 for splitter number 1, less than 0.08 for splitter number 2, less than 0.05 for splitter number 3) the relative sample flow rate $\dot{W}_S/\dot{W}$ is nearly the same (within 10%) for all three values of $\bar{G}$. As $\bar{X}$ increases, however, $\dot{W}_S/\dot{W}$ for the different values of $\bar{G}$ diverge. The $\dot{W}_S/\dot{W}$ for $\bar{G} = 1.5 \times 10^6$, initially 10% below the value for $\bar{G} = 1.0 \times 10^6$, falls considerably further below. For splitter number 1 it falls to 36% below at $\bar{X} = 0.23$, for splitter number 2 it falls to 31% below, and for splitter number 3 it falls to 26% below. The $\dot{W}_S/\dot{W}$ for $\bar{G} = 0.5 \times 10^6$, on the other hand, initially 2% below the value for $\bar{G} = 1.0 \times 10^6$, rises to 56% above at $\bar{X} = 0.35$.

Figure 21 shows the effect of $\bar{G}$ on the sample flow rate for all three splitters at $L_U = 8$. Again, at low values of $\bar{X}$, the relative sample flow rate $\dot{W}_S/\dot{W}$ is the same (within 5%) for all three values of $\bar{G}$. As $\bar{X}$ decreases toward zero, the curves all approach their respective single phase values. As $\bar{X}$ increases, $\dot{W}_S/\dot{W}$ for the different values of $\bar{G}$ diverge similar to Figure 20 ($L_U = 0$).

Starting with the smooth curves drawn through the data points of Figures 13 through 18, differences were taken and cross plots were prepared to yield the mass velocity in each of the three concentric regions shown in Figure 22, for particular values of $\bar{X}$, $\bar{G}$, and L_U . Some of the results are shown in Figures 23 through 26.

Figure 22. Identification of Concentric Regions

Figure 23. Mass Velocities in Concentric Regions,
 $G = 1 \times 10^6$ lb/h-ft², $L_U = 0$, Various $\bar{X}$.

Figure 24. Mass Velocities in Concentric Regions,
 $G = 1 \times 10^6$ lb/h-ft², $X = 0.05$, Various L_u .

Figure 25. Mass Velocities in Concentric Regions,
 $G = 1 \times 10^6$ lb/h-ft², $X = 0.15$, Various L_u .

Figure 26. Mass Velocities in Concentric Regions,
 $G = 1 \times 10^6$ lb/h-ft², $X = 0.25$, Various L_u .

Figure 23 shows the conditions just past the end of the heated length at $\bar{G} = 1.0 \times 10^6$ for three different qualities. It therefore represents conditions at three different positions along the heated length for the case that the exit quality is held constant. According to the flow regime maps of Reference 8, the two higher qualities are in the annular flow regime, and the lowest quality is in the bubbly flow regime. As the boiling flow proceeds along the channel from the bubbly flow regime toward annular regime, the mass velocities in Regions 1, 2, and 3 increase at the expense of Region 4. But as the boiling flow proceeds further along the channel, the mass velocity in Regions 1 and 4 increase at the expense of Regions 2 and 3. The net effect at the highest quality is that the mass velocities in all three Regions are close to the channel average $\bar{G}$.

Refer to Figure 24. At $\bar{G} = 1.0 \times 10^6$ and $\bar{X} = 0.05$ (corresponds to the bubbly/transition flow regime at $L_U = 0$, the slug regime at $L_U = 8$), the mass velocities in Region 1 (next to the wall) and Region 2 increase, whereas the mass velocity in Region 3 remains relatively constant and the mass velocity in Region 4 decreases, in the first two feet past the end of the heated length. The mass velocities in all four regions remain relatively constant past $L_U = 2$. Essentially all of the flow development takes place in the first two feet as noted earlier in the discussion of Figure 19. Associated with this development, mass is transferred from Region 4 through Region 3 to Region 2 and 1, and a slug flow regime becomes established.

At a higher flow rate ($\bar{G} = 1.5 \times 10^6$, $\bar{X} = 0.05$), the flow development proceeds in a similar way except that the mass velocity increases in Region 3 as well as in Regions 1 and 2, and a slug regime never becomes established.

Refer to Figure 25. At $\bar{G} = 1.0$ and $\bar{X} = 0.15$ (annular dispersed regime) the mass velocities in Region 1, Region 2, and Region 3 increase and the mass velocity in Region 4 decreases in the first two feet past the end of the heated length. The mass velocities in all four regions remain relatively constant past $L_U = 2$, the same as for Figure 24. Again, essentially all the flow development takes place in the first two feet. Mass is transferred from Region 4 to Regions 3, 2, and 1. The flow regime continues as annular dispersed after development, but the radial distribution of mass velocity has changed, being generally higher next to the wall, lower in the core.

Refer to Figure 26. At $\bar{G} = 1.0 \times 10^6$ and $\bar{X} = 0.25$ (annular dispersed) the mass velocities in Regions 1, 2, and 3 increase and the mass velocity in Region 4 decreases in the first two feet past the end of the heated length, the same as for Figure 25. When past $L_U = 2$ the mass velocities in Regions 2 and 3 decrease and the mass velocity in Region 4 increases, a reversal of the trend. The uncertainty interval on $\bar{G}$ is so wide (see Appendix A) that there is some uncertainty concerning this apparent change past $L_U = 2$. Nevertheless, this apparent behavior suggests the presence at higher values of $\bar{X}$, of a zone of liquid in the core adjacent to the film, which tends to diffuse both inward (toward center of core) and outward (toward wall) when conditions change abruptly from diabatic to adiabatic. When the concentration of liquid is reduced sufficiently by inward diffusion, then diffusion from Regions 2 and 3 to Region 4 can take place. Furthermore, there is no certainty that this process is completed at $L_U = 8$. The flow may not be fully developed at $L_U = 8$ for $\bar{X} \approx 0.25$ and higher.

4.2 SAMPLE QUALITY (SETUP NO. 1)

Data to determine isokinetic sample quality were obtained simultaneously with the measurements of isokinetic sample flow rate. These sample quality results are also listed in Table 4, and typical results are plotted in Figures 27 through 29, as sample quality X_S versus average channel quality $\bar{X}$. No attempt was made to fit smooth curves to the points. Uncertainty intervals for typical points show overlapping uncertainties, so only general trends can be discussed with confidence.

Consider Figure 27 (splitter number 1, $\bar{G} = 1.0 \times 10^6$, $L_U = 0, 2, 8$, and 23.8). For $L_U = 0$, the values of X_S obtained September 1970 tend to lie below the values obtained September 1969, by as much as 2 percentage points in the range $\bar{X} > 0.21$. Confidence bands show overlapping uncertainties. Though the differences do not appear random, the sets for the two dates show the same trends, and are considered in essential agreement. For $L_U = 2$ and 8 (and for all other splitters and flows) the values of X_S obtained September 1970 are in good agreement with the values obtained September 1969.

Continuing consideration of Figure 27, X_S for $L_U = 0$ and $-0.03 < \bar{X} < 0.21$ lies in the band $0.016 < X_S < 0.045$. It appears to be nearly constant, showing only a slight tendency to be: (1) high in the range $0 < \bar{X} < 0.12$, where the flow regime has been identified as bubbly, bubbly/transition, and transition/annular, and (2) low in the range $0.12 < \bar{X} < 0.21$, where the flow regime is annular dispersed. In the range $\bar{X} > 0.21$, X_S starts to increase with $\bar{X}$, reaching $X_S = 0.06$ at $\bar{X} \approx 0.30$.

Figure 27. Sample Quality versus Average Channel Quality,
 $G = 1 \times 10^6 \text{ lb/h-ft}^2$, Splitter No. 1, Various L_U

Figure 28. Sample Quality versus Average Channel Quality,
 $G = 1 \times 10^6 \text{ lb/h-ft}^2$, $L_u = 0$, Various Splitters.

Figure 29. Sample Quality versus Average Channel Quality,
 $G = 1 \times 10^6 \text{ lb/h-ft}^2$, $L_u = 8 \text{ ft}$, Various Splitters.

X_S for $L_U = 2$ and X_S for $L_U = 8$ are: (1) in good agreement with each other, and (2) lie consistently below X_S for $L_U = 0$. This generally characterizes X_S for the three different values of L_U for all the splitter numbers and values of $\bar{G}$, although for splitter number 3, X_S for $L_U = 2$ even lies below X_S for $L_U = 8$. (This seems anomalous, but is consistent with the slightly higher sample flow rate at $L_U = 2$ than at $L_U = 8$, as noted in Figure 19.) Higher sample densities can be associated with the lower values of X_S at $L_U = 2$ and 8. The greater sample flow rates at $L_U = 2$ and 8, noted in Figure 19, may be largely accounted for by higher densities.

X_S for $L_U = 23.8$ lies slightly (less than 1/2 percentage point) below X_S for $L_U = 8$ in the range $0.09 < \bar{X} < 0.29$, but as $\bar{X}$ increases beyond this range, X_S for $L_U = 23.8$ falls increasingly below. It is evident, as already suggested in the discussion of Figure 26, that for higher values of $\bar{X}$ the flow at $L_U = 8$ is not fully developed. In subsequent discussions, nevertheless, the results at $L_U = 8$ will serve as a basis of comparison as though the flow were fully developed, because of the limited number of data at $L_U = 23.8$.

Figure 27 showed the effect of L_U on the sample quality X_S . Figure 28 ($\bar{G} = 1.0 \times 10^6$, $L_U = 0$) and Figure 29 ($\bar{G} = 1.0 \times 10^6$, $L_U = 8$) show the effect of splitter number, i.e., the effect of splitter distance Δ , on X_S .

Consider Figure 28. At $\bar{X} = 0$, X_S is greater than zero for all three splitters but is lowest for splitter number 3 and highest for splitter number 1. It is evident that there is a concentration of subcooled voids within 0.0146 inch of the wall, but that the concentration diminishes as one moves to a position 0.032 inch away from the wall.

As $\bar{X}$ increases, X_S appears to go through a slight maximum, a slight minimum, then increases with $\bar{X}$. This was already noted for splitter number 1 in Figure 27. The increase in X_S starts at $\bar{X} = 0.09$ for splitter number 3, 0.15 for splitter number 2, and 0.21 for splitter number 1. For $\bar{X} > 0.12$, X_S is highest for splitter number 3 and lowest for splitter number 1; there is a concentration of liquid within 0.0146 inch of the wall, but the concentration diminishes as one moves away from the wall.

The results shown in Figure 29 for $L_U = 8$ are similar to the results shown in Figure 28 for $L_U = 0$. However, at $\bar{X} = 0$, X_S is zero. There are no subcooled voids. As $\bar{X}$ increases, X_S first increases slightly, remains constant for an interval (in contrast to Figure 28), then increases (the same as Figure 28). The increase for each of the three splitters starts at about the same values of $\bar{X}$ as in Figure 28. The principal difference between Figure 28 and Figure 29 is that for any given splitter and value of $\bar{X}$, the value of X_S in Figure 29 ($L_U = 8$) is consistently lower than the value in Figure 28 ($L_U = 0$). This difference was noted in the discussion of Figure 27. The consistently greater sample flow rates at $L_U = 8$, noted earlier, may be largely accounted for by higher densities associated with the lower sample qualities.

4.3 FLOW REGIME AND FILM THICKNESS (SETUP NO. 2)

4.3.1 Description of Results

Many observations were made with the conductivity probe, covering essentially the same range of conditions for which sample flow rate and quality data were obtained with Setup No. 1. In general, each observation was of a single oscilloscope trace, erased and repeated several times. Finally, one was selected which was judged characteristic for the particular flow conditions and distance of probe from the wall. The trace was recorded by means of a Polaroid oscilloscope camera. Some of the photos have been reproduced for this report, and are discussed in the following paragraphs.

Four different flow regimes (viz., the bubbly, slug, transition, and annular or annular/dispersed) were covered by the range of test conditions. The probe was located on the channel centerline for the slug flow runs, but was moved to the core/film interface for the annular flow runs. For each of a select number of the runs, a detailed traverse was made, and the oscilloscope trace was photographed at each position along the traverse. For many of the annular regime runs, however, no photographs were made; the only record kept was the measured film thickness.

The results, in terms of distance from end of heated length, pressure, flow rate, heat flux, quality, flow regime, and (in the case of annular flow) film thickness, are summarized in Table 5.

Figures 30, 31, and 32 are each a panel of photographs of oscilloscope traces* corresponding to different probe distances from the wall. For all three figures, the probe station is right at the end of the heated length ($L_U = 0$), the pressure is 1000 psia, the flow is 1.0×10^6 lb/h-ft², and the heat flux 0.55 to 0.57×10^6 Btu/h-ft². The qualities,

*These particular traces include some 60-cycle and 1000-cycle "noise" superposed on the signal of interest. The Figure 30 trace for $y = 0.001$ inch, for example, consists entirely of this noise. The usefulness of the pictures is not significantly affected by its presence.

Table 5
FLOW REGIME AND FILM THICKNESS DETERMINATIONS

Run No.	L_u (ft)	P (psia)	$\bar{G}/10^6$ (lb/h-ft ²)	$\phi/10^6$ (Btu/h-ft ²)	$\bar{X}$	Flow Regime*	δ (in.)
012	8	1005	1.027		0.297	A	0.010
013	↑	1007	1.025		0.393	↑	0.0035
011		1009	1.023		0.198	↓	0.0323
011.5		1005	1.025		0.240	↓	0.0172
010		1000	1.022		0.149	A	0.0522
007.25		1010	1.023		0.003	B	—
007.5		1000	1.022		0.023	S	
008		1009	1.017		0.049	S	
009		1005	1.023		0.104	S/A	
018		1013	1.536		0.310	A	0.0039
017		1010	1.538		0.200	↑	0.0232
017.5		1005	1.540		0.245		0.0103
018R		1015	1.538		0.293		0.0096
017.5R		1005	1.540		0.241		0.0246
017R		1003	1.538		0.199		0.0586
012R		1015	1.028		0.302		0.0173
013R		1000	1.023		0.404		0.005
011.5R		1000	1.030		0.238		0.0288
011R		995	1.022		0.206		0.043
012RA		1005	1.014		0.307		0.0118
011RA		1005	1.022		0.202		0.0407
018RA		1000	1.539		0.296		0.0091
017RA		995	1.532		0.203		0.0588
016		1000	1.531		0.153		0.1294
013RA		1005	1.027		0.397		0.0058
012RB	↓	1005	1.030		0.306		0.0133
012RC	8	1002	1.027		0.304		0.0136
039	0	1007	1.029	0.549	0.128		0.098
040	↑	1013	1.023	0.541	0.208		0.053
040.5		1013	1.031	0.546	0.232		0.035
040R		1019	1.027	0.559	0.181		0.1102
040RA		1033	1.026	0.533	0.180		0.1027
040.5R		1023	1.026	0.535	0.224		0.0864
033		1019	1.023	0.353	0.170		0.091
033R		1015	1.023	0.343	0.170		0.083
039R		1025	1.028	0.565	0.156		0.110
040RB		1019	1.020	0.556	0.191		0.0917
040.5R	↓	1015	1.026	0.567	0.267	↓	0.0598
041	0	1013	1.020	0.568	0.323	A	0.0089

- * 1 = Single phase with occasional bubbles
 B = Bubbly
 S = Slug
 T = Transition
 A = Annular or annular/dispersed

Table 5—(Continued)

Run No.	L_u (ft)	P (psia)	$\bar{G}/10^6$ (lb/h-ft ²)	$\phi/10^6$ (Btu/h-ft ²)	$\bar{X}$	Flow Regime*	δ (in.)
036	0 ↑	1011	1.024	0.559	-0.003	B	
035		1005	1.023	0.568	-0.009	1	
037		1013	1.028	0.567	0.050	B/T	
038		1007	1.023	0.555	0.099	T/A	
044		1003	1.024	0.745	-0.007	B	
047		1005	1.026	0.750	0.147	A	0.1054
029		1000	1.026	0.351	0.006	B	
033RA		1005	1.020	0.345	0.179	A	0.073
032		1000	1.019	0.345	0.138	↑	0.0883
060		1021	1.031	0.564	0.358		0.0015
059		1015	1.025	0.563	0.306		0.0064
056		1000	1.024	0.567	0.157		
040.5RB		1015	1.025	0.571	0.275		0.0112
040.5RC		1000	1.026	0.523	0.228	↓	
059R		1003	1.026	0.559	0.305	A	0.0054
020		1000	0.524	0.347	-0.015	1	
023		1003	0.514	0.350	0.129	T/A	0.060
024		1005	0.515	0.350	0.190	A	0.0385
024.5		1010	0.515	0.346	0.219	↑	0.031
025		1005	0.511	0.347	0.290		0.020
033RB		1015	1.022	0.352	0.175		0.0685
040.5RD		1015	1.026	0.565	0.269		0.019
041R		1017	1.026	0.559	0.299		0.0044
039RA	0 ↓	1001	1.026	0.564	0.165		0.0743
040RC		1015	1.024	0.565	0.201		0.0612
040.5RE		1018	1.025	0.570	0.270		0.019
059RA		1027	1.026	0.573	0.321		0.0061
033RC		1000	1.020	0.347	0.171		0.0653
011RC		1011	1.022		0.191		0.0329
011.5RA		1013	1.028		0.249		0.0171
012RC		1015	1.025		0.291	↓	0.0085
013RB		1017	1.032		0.393	A	0.0021
008R		1007	1.021		0.048	B/T	
009R		1009	1.018		0.099	B/T	
010R		1003	1.023		0.147	A	0.0676
014		1011	1.544		0.044	T	
015		1009	1.546		0.094	T	
016R		1002	1.537		0.149	A	0.0944
017RB		1000	1.542		0.203	↑	0.0383
017.5RA		1025	1.546		0.243	↓	0.009
018RB		1015	1.550		0.293	A	0.0027

- * 1 = Single phase with occasional bubbles
 B = Bubbly
 S = Slug
 T = Transition
 A = Annular or annular/dispersed

Table 5—(Continued)

Run No.	L_u (ft)	P (psia)	$\bar{G}/10^6$ (lb/h-ft ²)	$\phi/10^6$ (Btu/h-ft ²)	$\bar{X}$	Flow Regime*	δ (in.)
001	8 ↑	1013	0.521		0.041	S	
002		1003	0.520		0.098	S	
003		1013	0.518		0.142	S/A	0.0711
004		1009	0.518		0.196	A	0.0396
004.5		1009	0.530		0.228		0.0301
005		1011	0.525		0.286		0.0232
006	8 ↓	1015	0.515		0.392		0.0108
007		1013	0.523		0.572		0.0028
003R		1001	0.527		0.142		0.0607
042		1015	1.012	0.598	0.403		CHF
061		1015	1.540	0.605	0.262		CHF
042a		1000	1.030	0.608	0.183		0.0712
042b	0 ↑	1005	1.025	0.607	0.240		0.0228
042c		997	1.023	0.617	0.302		0.0037
042d		1015	1.022	0.613	0.332		0.0018
042e		1000	1.020	0.611	0.359		0.0010
042f		1003	1.018	0.611	0.369		0.0010
042g		1005	1.017	0.612	0.371		0.0008
042h		1013	1.021	0.614	0.378		0.0010
61A		1013	1.542	0.618	0.143		0.1204
61B		1009	1.537	0.621	0.198		0.0677
61C		1015	1.538	0.620	0.219		0.0667
61D		1005	1.536	0.620	0.240		0.0387
61E		1000	1.538	0.621	0.248		0.0284
61F		1013	1.544	0.617	0.246		0.0138
61G		1003	1.532	0.626	0.268		0.0112
60R	0 ↓	1015	1.536	0.565	0.192	A	0.0814

- * 1 = Single phase with occasional bubbles
 B = Bubbly
 S = Slug
 T = Transition
 A = Annular or annular/dispersed

Y = 0.001 INCH

Y = 0.020 INCH

Y = 0.060 INCH

Y = 0.090 INCH

Y = 0.003 INCH

Y = 0.030 INCH

Y = 0.120 INCH

Y = 0.180 INCH

Y = 0.010 INCH

Y = 0.045 INCH

Y = 0.240 INCH

Y = 0.341 INCH (CENTERLINE)

Figure 30. Bubbly Region from $y = 0.06$ inch to $y = R$, at near Zero Quality (Run No. 036, $L_u = 0$, $G = 1.02 \times 10^6$ lb/h-ft², $\phi = 0.56 \times 10^6$ Btu/h-ft², $\bar{X} = -0.003$).

Y = 0.003 INCH

Y = 0.030 INCH

Y = 0.090 INCH

Y = 0.270 INCH

Y = 0.010 INCH

Y = 0.045 INCH

Y = 0.150 INCH

Y = 0.341 INCH (CENTERLINE)

Y = 0.020 INCH

Y = 0.060 INCH

Y = 0.210 INCH

Figure 31. Bubbly Region from $y = 0.06$ inch to $y = 0.20$ inch, Transition Region from $y = 0.20$ inch to $y = R$ (Run No. 037, $L_u = 0$, $G = 1.03 \times 10^6$ lb/h-ft², $\phi = 0.57 \times 10^6$ Btu/h-ft², $\bar{X} = 0.050$).

Y = 0.003 INCH

Y = 0.030 INCH

Y = 0.060 INCH

Y = 0.210 INCH

Y = 0.010 INCH

Y = 0.045 INCH

Y = 0.090 INCH

Y = 0.341 INCH (CENTER LINE)

Y = 0.020 INCH

Y = 0.150 INCH

Figure 32. Annular Dispersed Flow (Run No. 056, $L_u = 0$, $G = 1.02 \times 10^6$ lb/h-ft², $\phi = 0.57 \times 10^6$ Btu/h-ft², $\bar{X} = 0.157$).

however, are different for the three figures, being respectively -0.003 , $+0.050$, and $+0.147$. The corresponding regimes are respectively bubbly, bubbly/transition, and annular. Figure 30 (bubbly regime) shows almost complete absence of bubbles in the region from wall to $y = 0.060$ inch, but fairly uniformly distributed bubbles inside of $y = 0.060$ inch; i.e., for $y > 0.060$ inch. This observation is in apparent contradiction to the evidence presented earlier in the discussion of Figures 14 and 28, that subcooled voids are present close to the wall at near zero quality. But the structure of these subcooled voids is too fine (individual voids must be much smaller than the exposed metal tip of the probe) to interfere with the continuous liquid bridge from probe to wall.

Figure 31 (bubbly/transition) also shows very few bubbles from wall to $y = 0.060$ inch, but shows rapidly increasing bubbles inside of this, to $y = 0.20$ inch. Inside of $y = 0.20$ inch, the regime appears to be entirely transition; i.e., neither the liquid nor the vapor phase appear to be continuous.

Figure 32 shows bubbles next to the wall, the interface at about $y = \delta = 0.09$ inch, and a continuous vapor phase in the core region. This is definitely the annular or annular/dispersed regime.

There was no evidence of slug flow right at the end of the heated length, regardless of quality, for any flow in the range $0.5 \times 10^6 \leq G \leq 1.5 \times 10^6$ lb/h-ft². There was no evidence of slug flow even 8 feet past the end of the heated length ($L_u = 8$) for $G = 1.5 \times 10^6$ lb/h-ft². However, for $G = 1.0 \times 10^6$ lb/h-ft², qualities 0.02 to 0.10 (Figure 33), and $G = 0.5 \times 10^6$ lb/h-ft², qualities 0.04 to 0.14 (Figure 34) slug flow was in evidence 8 feet past the end of the heated length. The slug flow vanished as the quality increased. Two of the runs ($G = 1 \times 10^6$ lb/h-ft², qualities 0.05 and 0.10) when repeated, showed bubbly/transition and transition rather than slug flow. It is evident that at $L_u = 8$ and $\bar{G} = 1.5 \times 10^6$ the slug regime never occurs, at $\bar{G} = 1.0 \times 10^6$ the slug regime occurs (when the quality is right) but enjoys a somewhat tenuous existence, and at $\bar{G} = 0.5 \times 10^6$ the slug regime becomes well established.

The foregoing observation of flow regime are in essential agreement with observations by Bugles, et al.⁸

A film thickness could be determined both at the end of the heated length and 8 feet past the end, for all three flows and at qualities in excess of about 0.13. The results are plotted in Figures 35, 36, and 37, for $\bar{G} = 0.5 \times 10^6$, 1.0×10^6 , and 1.5×10^6 lb/h-ft², respectively.

Referring to Figure 35 for $\bar{G} = 0.5 \times 10^6$ lb/h-ft² and qualities in excess of 0.15, the film thickness is apparently independent of distance from the end of the heated length. At qualities near CHF, this is known not to be so (the film thickness right at the end of a uniformly heated circular tube goes to zero at CHF, whereas it will not generally be zero under adiabatic conditions except at qualities approaching 1.0)⁶. But it is evidently true for this particular test channel at this particular flow and pressure in the range of film thickness from 0.05 inch to 0.02 inch, qualities from 0.15 to 0.30. This is an unexpected result. Sample flow data indicate that the mass flow rate in the film region increases with increasing distance from the end of the heated length. The fraction of vapor carried in the film region must therefore decrease with increasing distance from the end of the heated length, at least for a distance of 8 feet. The sample quality data agree with this conclusion.

Referring to Figure 36, for $\bar{G} = 1.0 \times 10^6$ lb/h-ft² and qualities 0.15 to 0.30, the film thickness is even greater right at the end of the heated length than at 8 feet past. This, again, is unexpected. Assuming, that the film flow rate right at the end of the heated length is the same or less than at eight feet past, it leads to reinforcement of the conclusion—at least for the quality range from 0.15 to 0.30—that the fraction of vapor carried in the film must decrease with increasing distance. Again, the sample quality data agree with this.

Referring again to Figure 36, it will be noted that for qualities in excess of 0.30, on the other hand, the film thickness is less at the end of the heated length than it is 8 feet past. In this case, the film at the end of the heated length is near a CHF condition. If the curve of Figure 36 for $L_u = 0$ were extrapolated to zero film thickness, it would intersect the $\bar{X}$ axis at almost the exact quality at which CHF was observed, thus confirming that the film under heat transfer conditions goes to zero at CHF. No conclusions can be drawn about changes in the relative amount of vapor carried in the film with increasing distance from the end of the heated length when conditions are near CHF. However, it is probable that when the film is this thin (in the order of 0.005 inch or less), very little vapor is carried.

Referring to Figure 37, for $\bar{G} = 1.5 \times 10^6$ lb/h-ft² and qualities 0.15 to 0.25, the film thickness is again greater at the end of the heated length than at 8 feet past. The same conclusion can be drawn as for the two lower flows, concerning decrease in fraction of vapor carried in the film with increasing distance. It will be noted that CHF occurred at a lower quality than would be predicted from an extrapolation of the smooth curve through the data for $L_u = 0$. Bergles, et al.,⁸ observed a similar behavior at higher flows for some of their test runs. Disruption of the film tends to occur abruptly at higher flows as CHF is approached.

RUN NO. 7.5, $\bar{X} = 0.023$
20 msec SWEEP

RUN NO. 8, $\bar{X} = 0.049$
20 msec SWEEP

RUN NO. 9, $\bar{X} = 0.104$
20 msec SWEEP

RUN NO. 9R, $\bar{X} = 0.099$
5 msec SWEEP

Figure 33. Evidence of Slug Flow Diminishes as Quality Increases (Probe on Centerline, $L_u = 8$ ft, $G = 1.02 \times 10^6$ lb/h-ft²). No Slug Flow Was Observed for Run No. 009.R.

 $\bar{X} = 0.041$, 5 msec SWEEP

 $\bar{X} = 0.041$, 10 msec SWEEP

 $\bar{X} = 0.041$, 50 msec SWEEP

 $\bar{X} = 0.098$

 $\bar{X} = 0.098$

 $\bar{X} = 0.142$
5 msec SWEEP

 $\bar{X} = 0.142$
50 msec SWEEP

Figure 34. Appearance of Oscilloscope Trace at Different Sweep Rates, Under Slug Flow Conditions (Probe on Centerline, $L_u = 8$ ft, $G = 0.52 \times 10^6$ lb/h-ft², Run No. 001, $\bar{X} = 0.041$; Run No. 002, $\bar{X} = 0.098$; Run No. 003, $\bar{X} = 0.142$). Evidence of Slug Flow Diminishes as Quality Increases.

Figure 35. Film Thickness versus Average Channel Quality
($G = 0.5 \times 10^6$ lb/h-ft²).

Figure 36. Film Thickness versus Average Channel Quality
($G = 1.0 \times 10^6$ lb/h-ft²).

Figure 37. Film Thickness versus Average Channel Quality ($G = 1.5 \times 10^6 \text{ lb/h-ft}^2$).

All the best-fit curves through the data of Figures 35, 36, and 37 have been superposed on Figure 38, to facilitate comparison. Referring to Figure 38, and considering the curves for $L_u = 8$, the film thickness at qualities less than 0.18 *increases* with increasing channel flow rate. At qualities greater than 0.22, the trend reverses, and the film thickness *decreases* with increasing channel flow rate. Considering the curves for $L_u = 0$, the trend in film thickness with channel flow rate is essentially the same as for $L_u = 8$, but the reversal in trend occurs at slightly higher qualities.

The effective positions of the splitters used for taking off film flow samples isokinetically in Setup No. 1 are shown in Figure 38. If the film thickness is less than the splitter distance, the sample must include core flow as well as film flow, and the sample quality must increase. A comparison of Figure 38 with Figures 28 and 29 shows that the sample quality increases rapidly when the measured film thickness becomes less than the distance from wall to splitter. It is evident from these considerations that the conductivity probe is determining the film thickness correctly.

At some value of $\bar{X} = \bar{X}_\Delta$, the thickness of the film is equal to the splitter distance. The sample flow rate is then equal to the film flow rate as hereinafter defined. This value of film flow may be less than would be measured by the suction techniques employed by Hewitt⁵ and others, because of the flow carried in the crests of waves which are cut off by the splitter. Nevertheless the sample flow rate at $\bar{X} = \bar{X}_\Delta$ will be referred to as film flow rate in ensuing discussions.

The film flow rate is plotted versus $\bar{X}$ in Figure 39. This reveals the unexpected result that the film flow rate at $\bar{G} \geq 1 \times 10^6$ lb/h-ft² is greater under heat transfer conditions ($L_u = 0$) than under adiabatic conditions ($L_u = 8$) (except for $\bar{X}$ near CHF, which has been noted before in discussion of film thickness). The film at the higher flows and $L_u = 0$ is characterized both by greater thickness and higher void compared with the film at $L_u = 8$. The thickness is greater at $L_u = 0$, therefore the film flow rate is greater than at $L_u = 8$, in spite of the voids.

At $\bar{G} = 0.5 \times 10^6$ lb/h-ft², on the other hand, the film flow rate is less under heat transfer conditions, which is directly related to the fact that at this low flow the thickness at $L_u = 0$ is the same as the thickness at $L_u = 8$.

4.3.2. Comparison with Results of Others

A direct comparison with most of the film thickness results obtained at Dynatech by Bergles, et al.,⁸ cannot be made, because their data were obtained under different conditions; e.g., different channel diameter, generally different flow rates, heat flux not constant. Nevertheless, certain Dynatech data have been superposed on Figure 38, for a channel diameter of 0.40 inch, heated length 58 inches, pressure 1000 psia, mass velocity 0.8×10^6 lb/h-ft². The Dynatech data are qualitatively in very good agreement with the results obtained on this program, being approximately parallel to, but about 50% higher than, the Figure 38 curve for $G = 0.5 \times 10^6$ lb/h-ft². The same trends which are seen in the data reported here, can be seen in this Dynatech data, namely: (1) as CHF is approached the film thickness becomes less under boiling conditions than under adiabatic conditions; (2) away from CHF the film thickness is greater under boiling conditions than under adiabatic conditions. The Dynatech people did not measure any quantity which could be interpreted directly as void, but it is clear from the results reported here that the void content in their film under boiling conditions was higher than under adiabatic conditions.

4.4 PRESSURE DROP (SETUP NO. 1)

The single-phase pressure drop results have already been presented in Section 2.2.4 Single Phase Friction Factor. Pressure drop was also measured under two-phase conditions, both adiabatic and with heat addition. The adiabatic data are listed in Table 6, the data with heat addition in Table 7.

The pressure drop listed in Table 6 is the measured drop corrected for hydrostatic head, using the Martinelli-Nelson void correlation.⁹ The ratio of two-phase to single-phase pressure loss is also listed in Table 6, and compared with the Martinelli-Nelson multiplier in Figure 40. The measured ratio is 25 to 35% below the Martinelli-Nelson value. This is consistent with the two-phase adiabatic pressure drop results reported by Janssen and Kervinen¹⁰ for round pipes and rectangular channels.

The pressure drop listed in Table 7 is the total pressure drop; i.e., it includes friction, hydrostatic head, and acceleration. The reference pressure tap P1 was located at the beginning of the heated length. For runs 15 through 20 the heated length was reduced to six feet, so that the last tap (P8) was located one foot past the end of the heated length, in the unheated length. The values of $P_{(ref)} - P$ for this last tap are suspect because they seem too low, but nothing wrong could be found with the tap itself.

Figure 38. Film Thickness versus Average Channel Quality, Various Flows.

Figure 39. Ratio, Film Flow Rate to Total Flow Rate versus Average Channel Quality.

Figure 40. Two-Phase Multiplier versus Average Channel Quality, Martinelli-Nelson Multiplier Curve Superposed.

Table 6

TWO-PHASE ADIABATIC PRESSURE DROP

Run No.	L_u (ft)	P (psia)	$\bar{G}/10^6$ (lb/h-ft ²)	$\bar{X}$	$\Delta P_{TPF}/\Delta Z$ (lb/ft ³)	$\Delta P_{TPF}/\Delta P_F$
6	8	1002	1.501	0.0581	41.77	2.883
7	8	997	1.507	0.1071	58.62	4.017
8	8	1023	1.524	0.1886	78.60	5.281
9	8	995	1.021	0.2487	50.02	6.777
10	8	989	1.018	0.1985	43.37	5.906
11	8	1011	1.015	0.1000	28.86	3.951

Table 7

TWO-PHASE PRESSURE DROP WITH HEAT ADDITION

Run No.	L _H (ft)	P (psia)	$\bar{G}/10^6$ (lb/h-ft ²)	$\phi/10^6$ (Btu/h-ft ²)	Δh_s (Btu/lb)	$\bar{X}_e$	Z - Z _(REF) (in.)						
							12-1/8	24-1/4	36-3/8	48-1/2	60-5/8	72-3/4	84-7/8
							P _(REF) - P (psf)						
12	8	999	1.529	0.550	169.7	0.0472	64.50	133.3	205.8	—	357.2	452.2	561.4
13	8	993	1.529	0.550	134.1	0.1018	76.38	142.8	216.2	—	394.7	508.5	629.4
14	8	1009	1.514	0.554	64.3	0.2156	83.42	170.8	277.9	—	533.4	696.1	—
15	6	1005	1.015	0.557	99.7	0.1990	61.58	134.5	206.0	—	402.9	507.7	535.2
16	6	995	1.012	0.565	157.2	0.1093	61.81	123.2	191.6	—	337.0	433.8	465.6
17	6	1002	1.016	0.561	194.8	0.0545	60.85	122.1	183.9	—	324.8	404.2	434.4
18	6	1005	1.008	0.565	228.0	0.0088	60.11	122.1	184.4	—	309.2	395.7	424.8
19	6	1010	1.012	0.565	259.1	-0.0406	61.50	123.6	185.9	—	310.7	385.9	425.5
20	6	1000	1.513	0.559	41.0	0.1742	96.80	208.8	324.0	—	622.8	—	—

5. CONCLUSIONS, PART I

The following summarizes the findings and conclusions with respect to the experimental results of Part I. Specific conclusions apply strictly to the test geometry and conditions. The trends noted have more general validity.

1. The mass flow rate in the zone next to the wall under boiling conditions ($L_U = 0$) and average channel qualities $\bar{X}$ near zero, is less than under single phase conditions. There are subcooled voids next to the wall for $\bar{X}$ near zero. The thickness of the zone thus affected is not less than 0.0225 inch at $\bar{G} = 1.0 \times 10^6$ lb/h-ft², and not less than 0.032 inch at $\bar{G} = 1.5 \times 10^6$ lb/h-ft².
2. The mass flow rate in the zone next to the wall increases as $\bar{X}$ increases, until it exceeds the mass flow rate under single phase conditions. The liquid phase tends to concentrate close to the wall at higher values of $\bar{X}$.
3. The mass flow rate in the zone next to the wall under adiabatic conditions ($L_U = 2$ and $L_U = 8$) is greater than under either single phase conditions or boiling conditions ($L_U = 0$) for all $\bar{X}$.
4. Significant radial transfer of mass (as much as 5% of the total mass flowing) takes place from the interior region to the zone next to the wall as the total flow moves from the end of the heated length ($L_U = 0$) to two feet past the end ($L_U = 2$).
5. The local quality in the zone next to the wall under boiling conditions ($L_U = 0$) is consistently above the local quality under adiabatic conditions ($L_U = 2$ and $L_U = 8$). This is consistent with the presence of subcooled voids at $\bar{X} = 0$, and the generally higher mass rates in the zone next to the wall at $L_U = 2$ and $L_U = 8$, compared with $L_U = 0$. The greater sample flow rate at $L_U = 2$ and 8 can be largely accounted for by the higher densities associated with the lower sample qualities at $L_U = 2$ and 8. The fraction of vapor carried in the film decreases with increasing distance past the end of the heated length.
6. For $\bar{X} < 0.15$, the two phase flow is essentially fully developed in the first two feet past the end of the heated length. For $\bar{X} > 0.29$, the flow may not become fully developed in the first eight feet past the end of the heated length.
7. The relative sample flow rate $\dot{W}_s/\dot{W}$ under both boiling and adiabatic conditions for low values of $\bar{X}$ is nearly independent of $\bar{G}$. However, for $\bar{X} > 0.05$ to 0.12, $\dot{W}_s/\dot{W}$ is flow dependent, being higher at lower values of $\bar{G}$.
8. The subcooled voids which are present in the zone next to the wall for $\bar{X}$ near zero, are too fine to be detected by the conductivity probe.
9. The observations of flow regime are in essential agreement with the observations of Bergles, et al.⁸
10. The film thickness measurements are in qualitative agreements with results obtained by Bergles, et al, and show similar trends.
11. The film thickness at $\bar{G} > 0.5 \times 10^6$ lb/h-ft² under boiling conditions ($L_U = 0$) is greater than under adiabatic conditions except for $\bar{X}$ near CHF. This greater thickness at $L_U = 0$ may be associated with higher voids.
12. The film thickness under both boiling and adiabatic conditions *increases* with increasing $\bar{G}$ for $\bar{X} < 0.18$ to 0.24, and *decreases* with increasing $\bar{G}$ for $\bar{X} > 0.22$ to 0.26.
13. Defining the film flow rate as equal to the sample flow rate at conditions for which the splitter distance Δ is equal to the film thickness δ (determined with conductivity probe); (a) the film flow rate at $\bar{G} = 0.5 \times 10^6$ lb/h-ft² is less under boiling conditions than under adiabatic conditions; (b) the film flow rate at $\bar{G} \geq 1.0 \times 10^6$ lb/h-ft² is greater under boiling conditions (in spite of higher voids) than under adiabatic conditions, except for $\bar{X}$ near CHF.
14. The ratio of adiabatic two-phase to single phase frictional pressure drop is 25% to 35% below the Martinelli-Nelson value.⁹

These findings and conclusions have significance for devising or evaluating models of developing two-phase flow, particularly in the film region, and particularly for high pressure systems. Further generalization of the results and comparison with certain CISE argon-water and argon-alcohol data is deferred to Part II.

PART II
ANALYTICAL STUDIES, TUBES AND ANNULI

H.T. Kim

1. SUMMARY, PART II

1.1 CIRCULAR TUBE

The flow rate in the liquid film for $y \leq \delta$ for fully developed adiabatic two-phase annular flow in a circular tube was analyzed. It was assumed that; (1) the film mean velocity is described by the Prandtl mixing length model for single phase flow, and (2) the void distribution in the film is a function of U^+ . The analysis yielded $G_{\ell f}^+$ as a function of y^+ ($\leq \delta^+$). The sample flow and sample quality data for $y \leq \delta$ and $L_U = 8$ reported in Part I were compared with the model. Agreement between the data and the prediction is satisfactory (75% of data lie within $\pm 15\%$ of prediction).

The steam-water sample flow data ($L_U = 8$) for $y < \delta$ as well as $y = \delta$ are correlated quite well by the film thickness - film flow rate relationship first proposed by Alia, et al, namely, $G_{\ell f}^+ = 5.3(y^+)^{1/3}$, which was based on the CISE adiabatic fully developed film data for $y = \delta$ (argon-water and argon-alcohol mixtures). This is additional evidence that $G_{\ell f}^+$ is a unique function of $y^+ (\leq \delta^+)$, provided that the flow is fully developed.

However, the relationship by Alia, et al, does not apply to the diabatic data. The diabatic data taken at $L_U = 0$ exhibit effects of flow, quality, and heat flux on the film thickness-film flow rate relationship. These data are correlated with the adiabatic data by the following simple function

$$\frac{(G_{\ell f}^+)_d}{(G_{\ell f}^+)_a} = 1 - 3 \left(\frac{\phi}{10^6} \right) \left(\frac{\bar{G}}{10^6} \right) \quad \text{X}$$

1.2 ANNULUS

An expression for the net interchange rate of liquid droplets between core and liquid film regions, for developing adiabatic two-phase annular flow in vertical annuli was derived. The net interchange process rate is proportional to the departure of the film from its equilibrium state, as well as being a function of various system variables. The analysis shows that the liquid film flow rate (both rod and tube) approaches its equilibrium value asymptotically.

The model was compared with the rod and tube film growth data of Moeck for developing adiabatic steam-water flow in a vertical annulus at high pressures. The predictions compare favorably with the measured values (80% to 85% of the data lie within $\pm 15\%$ of prediction).

Both analysis and annulus data indicate that the higher the mass flow and the pressure and the lower the quality, the longer the developing length will be. This quality effect is in contrast with that indicated by the circular tube data of Part I.

The analytical approach used in the present study may be extended to formulate a CHF model which predicts the "dryout" point at which boiling heat transfer in the annular regime breaks down.

2. TUBE

Fully developed two phase annular flow in a circular tube will be considered in this section. The analysis deals with the flow characteristics within the liquid film region next to the tube wall. The model will be compared with some of the data of Part I and also some CISE data^{1,2}. In addition, the difference between adiabatic and diabatic film characteristics will be discussed.

2.1. ANALYSIS

An attempt will be made to predict the sample flows measured for fully developed adiabatic two-phase annular flow in the circular tube of Part I, where the annular zones formed by the splitters are located in the liquid film region.

Mass flux of the sample flow is calculated from

$$G_S = \frac{1}{\Delta} \int_0^{\Delta} \rho U dy, \Delta \leq \delta \quad (22)$$

Introducing void-weighted two-phase density and wall parameters, and assuming zero local slip, Equation 22 can be rewritten as

$$G_S^+ \equiv \frac{G_S \Delta}{\mu_l} = \int_0^{\Delta^+} (1-\alpha) U^+ dy^+ + \frac{\rho_g}{\rho_l} \int_0^{\Delta^+} \alpha U^+ dy^+ = G_{lS}^+ + G_{gS}^+ \quad (23)$$

where

$$X_S = \frac{G_{gS}^+}{G_S^+}$$

Both velocity and void fraction profiles in the film region must be specified in order to perform the integration indicated in Equation 23. In the present analysis, the single-phase "law of the wall" of the mean velocity profile is assumed to apply to the liquid film region, namely (1) a viscous sublayer ($y^+ \leq 11$) and (2) a fully turbulent layer described by the Prandtl mixing length theory.

Several investigators (Alia, et al;^{1,2} Biasi;^{1,3} Simpson^{1,4}) have suggested that the non-dimensional film liquid flow rate, G_{lf}^+ is a unique function of δ^+ . Moreover, film data of Alia, et al, indicate that the G_{lf}^+ between the wall and a given y^+ in the film also follows the same unique functional relation until y^+ is greater than δ^+ .

To be consistent with the U^+ and G_{lf}^+ being unique functions of y^+ , Equation 23 then suggests that α is also a unique function of y^+ . Following Simpson,^{1,4} the following form of void fraction profile has been assumed in the present analysis:

$$\begin{aligned} \alpha &= 0 \text{ for } y^+ \leq 11 \\ \alpha &= A(U^+ - 11) \text{ for } y^+ > 11 \end{aligned} \quad (24)$$

In the viscous sublayer for $y^+ \leq 11$,

$$\tau_W = \mu \frac{\partial U}{\partial y} \quad (25)$$

With $\alpha = 0$ in the sublayer, the classical single-phase relation is obtained, i.e.,

$$\frac{U}{V^*} = \frac{yV^*}{\nu_l} \text{ or } U^+ = y^+ \quad (26)$$

For the fully-developed region, the shear stress is expressed in terms of effective two-phase eddy viscosity;

$$\tau = (\mu_2 \phi + \epsilon_2 \phi) \frac{\partial U}{\partial y} \quad (27)$$

where $\epsilon_2 \phi = \rho_l^2 \frac{\partial U}{\partial y}$. Assuming $\mu_2 \phi \ll \epsilon_2 \phi$ and $\tau = \tau_W$, and using relations $\rho = \rho_l(1 - \alpha) + \rho_g \alpha$ and $l = \kappa y$, Equation 27 can be rewritten as

$$\frac{dy^+}{\kappa y^+} = \sqrt{1 - \left(\frac{\rho_l - \rho_g}{\rho_l} \right) A (U^+ - 11)} dU^+ \quad (28)$$

Using the single phase value for $\kappa = 0.4$, and setting $\frac{\rho_l - \rho_g}{\rho_l} = 0.9515$ corresponding to $p = 1000$ psia, integration of Equation 28 yields

$$U^+ = \frac{1.05}{A} \left\{ 1 - \left(1 - 3.57 A \ln \frac{y^+}{11} \right)^{2/3} \right\} + 11 \quad (29)$$

Equations 24, 26, and 29 were substituted in Equation 23 to calculate the sample flow rate and quality of the sample flow. The coefficient A in Equation 24 was adjusted so that the best fit to the test data was obtained by the model. From this study, the coefficient A was found to be 0.045.

2.2 Comparison of Model with Experimental Results

The value of G_{sf}^+ predicted by the model is plotted as a function of y^+ in Figure 41. The sample flow data from Part I ($y^+ \leq \delta^+$) are superposed for comparison. All the data points lie within $\pm 25\%$ of the model prediction; 75% of the points lie within $\pm 15\%$ of the prediction. They tend to be slightly low with respect to the prediction at the lower values of y^+ , and slightly high at the higher values of y^+ , i.e., the slope of the data is slightly greater than the slope of the prediction. Evidently the value of α used by the model is slightly high or the value of U^+ is slightly low at the higher values of y^+ , and vice versa at the lower values of y^+ .

Although the lower flow points tend to be at the lower values of y^+ and the higher flow points at the higher values of y^+ , no clear flow effect is apparent in Figure 41.

Most of the data points plotted in Figure 41 are for $y^+ < \delta^+$, i.e., they are for only a fraction of the film, and that fraction is next to the wall. The points for $y^+ = \delta^+$ are for the entire film as determined in Part I. These latter points lie generally within the scatter of the data, but tend to be low. The voids in the film next to the interface are evidently slightly higher than the value used by the model. Nevertheless, Figure 41 shows that the model is in reasonably good agreement with the data.

As a further comparison between model and experiment, predicted values for the sample flow rate and the sample quality at $\bar{G} = 0.5 \times 10^6$, 1.0×10^6 , and 1.5×10^6 have been plotted in Figures 42, 43 and 44, respectively, and the measured values from Part I superposed. The effective splitter dimensions, as determined in Part I, were used in the calculations. It was observed that the predicted curve of sample flow splitter Number 1 is high with respect to the data. The calculations were then repeated using the measured splitter dimensions. There was very little change in the predicted curves for splitter Numbers 2 and 3, but the curve for Splitter Number 1 was lowered by 18%, which brought it into much better agreement with the data. The predicted sample flow, based on measured splitter dimensions, is in reasonably good agreement with the data for all three splitters, but based on effective splitter dimensions is in good agreement with the data for only splitter Numbers 2 and 3. This suggests that the basis for determining the effective splitter dimensions, i.e., the dimensions which give the observed single phase sample flow rate at $P_W - P_C = 0$, assuming the "law of the wall" holds, is inadequate. The single phase data were obtained largely at Reynolds number $< 70,000$. P_W may be affected by Reynolds number in such a way that at very high values of Reynolds number ($N_R \approx 10^6$) the effective splitter dimensions more nearly coincide with the measured dimensions.

Neither the predicted curves nor the data of Figures 42, 43, and 44 were plotted beyond the value of $\bar{X}$ at which $y^+ = \delta^+$ (see Figure 38). The predicted curves continue to rise, with increasing $\bar{X}$, right up to the termination point. The data, on the other hand, particularly for splitter Numbers 2 and 3 at the two higher flows, show indications of reaching or passing through a maximum. This evidence is related to that presented in the discussion of Figure 41, to the effect that the voids in the film next to the interface are slightly higher than the value used by the model.

Finally, referring again to Figures 42, 43, and 44, the predicted sample quality is high with respect to the data, particularly at the higher flows. The confidence bands on sample quality are quite wide (the order of ± 0.03), but the sample quality data are consistently below the prediction, by the same order of magnitude. It is evident that the value of α used by the model at the two higher flows is too high.

Figure 41. Nondimensional Mass Velocity of Liquid Phase in Film Region G_{lf}^+ versus Nondimensional Distance from Wall y^+

Figure 42. Predicted Sample Flow Rate and Sample Quality Compared with Experimental Values ($\bar{G} = 0.5 \times 10^6 \text{ lb/ft}^2$).

Figure 43. Predicted Sample Flow Rate and Sample Quality Compared with Experimental Values ($G = 1.0 \times 10^6 \text{ lb/h-ft}^2$).

Figure 44. Predicted Sample Flow Rate and Sample Quality Compared with Experimental Values ($G = 1.5 \times 10^6 \text{ lb./h-ft}^2$).

2.3 Adiabatic and Diabatic Film Thickness—Film Flow Rate Relationships

We return to the $G_{\ell f}^+$ vs. y^+ plane in Figure 45, to compare some of the sample data from Part I with CISE data.^{1,2} The CISE data were obtained with pressurized argon-water and argon-alcohol ($\rho_g = 36.1 \text{ g/cm}^3$, same as saturated steam at 1000 psia) in a 2.5 cm i.d. tube. A scoop-like probe was used which could traverse the film region continuously from $y = 0.13 \text{ mm}$ to $y = 2 \text{ mm}$ (0.005-inch to 0.080 inch). The probe functioned in a manner identical to the flow splitters of Part I; the samples were obtained under isokinetic conditions. The CISE film thickness was measured by an electrical conductance scheme. The CISE data in Figure 45 were obtained when the probe was inserted a distance just equal to the film thickness as determined electrically. The CISE film thickness determined in this way is expected to be less than the thickness determined by the conductivity probe method of Part I. The CISE data are compared in Figure 45 with all of the adiabatic ($L_U = 8$) sample data of Part I for which $y^+ \leq \delta^+$. All of the points of Figure 41 are replotted on Figure 45.

Referring to Figure 45, both the CISE data and the adiabatic ($L_U = 8$) steam-water data of Part I are correlated by the expression first proposed by Alia, et al,^{1,2} for $y^+ = \delta^+$,

$$G_{\ell f}^+ = 5.3(y^+)^{1.1} \quad (30)$$

This correlation fits 80% of the Part I adiabatic data points to within $\pm 15\%$. The good agreement with both CISE data and Part I data is strong evidence that $G_{\ell f}^+$ is indeed a unique function of y^+ , provided the flow is fully developed. For any fully developed case, then, given the film thickness, the film liquid flow rate can be predicted from this relationship.

On the other hand, if the flow is not fully developed the relationship between film thickness and film flow rate given by Equation 30 is no longer expected to apply. Part I steam-water data for $L_U = 0$ have been plotted in Figure 46, and the Equation 30 correlation superposed, to show the effect of boiling on the $G_{\ell f}^+$ versus y^+ relationship. These diabatic points lie consistently below the correlating line for the adiabatic data, by as much as 65%. The void content is significantly greater in the diabatic film than in the corresponding adiabatic film, particularly at high flows and high qualities. There is obviously both a flow effect and a quality effect. Moreover, there must also be a heat flux effect (when the heat flux approaches zero the points must approach the adiabatic line), though most of the data were taken only at heat fluxes in the range $0.50 \times 10^6 < \phi < 0.57 \times 10^6 \text{ Btu/h-ft}^2$.

The diabatic points are related to the adiabatic correlation by the following relationship;

$$\frac{(G_{\ell f}^+)_d}{(G_{\ell f}^+)_a} = f(\bar{G}, \bar{X}, \phi) \quad (31)$$

There may also be geometry effects, pressure effects, etc., but if we limit our attention to the circular tube case of Part I, we can get good agreement with the diabatic data by the simple function

$$f = 1 - K \left(\frac{\phi}{10^6} \right) \left(\frac{\bar{G}}{10^6} \right) \bar{X} \quad (32)$$

By setting $K = 3$, the plot of Figure 47 results, all but three of the diabatic points lie within $\pm 15\%$ of the correlation.

The function of Equation 32 must be used with caution. In particular the effect of heat flux is not known except at the two values $\phi = 0$ and $\phi = 0.5$ to $0.57 \times 10^6 \text{ Btu/h-ft}^2$. But Equation 32 suggests that if any one of the three parameters ϕ , $\bar{G}$, or $\bar{X}$ are low, the film liquid flow rate becomes indistinguishable from the adiabatic case.

Figure 45. G_{qf}^+ versus y^+ . Adiabatic Data from Part I Compared with CISE Correlation.

Figure 46. $G_{\theta f}^+$ versus y^+ . Diabatic Data from Part I Compared with CISE Correlation.

Figure 47. $G_{qf}^+ / 1 - 3 (\phi/10^6) (\bar{G}/10^6) \bar{X}$ versus y^+ . Diabatic Data from Part I Compared with Modified CISE Correlation.

3. ANNULUS

Adiabatic developing two phase annular flow will be considered in this section. The analysis deals with the process of liquid droplet interchange between the core and the liquid film. The analysis was generalized by considering an annulus. The circular tube case can be treated by simplifying the analysis, but will not be specifically considered here. The model will be compared with some of annulus data of Moeck¹¹ for adiabatic developing two phase flow.

3.1 BASIC EQUATIONS FOR LIQUID FILM FLOWS

Consider Figure 48, which shows an idealization of annular dispersed flow in a concentric annulus. The mass balances on the inner and outer liquid films are:

Inner Film

$$\frac{dG_{If_i}}{dz} = (W_{D_i} - W_{E_i}) \frac{4(D_i + 2\delta_i)}{(D_o^2 - D_i^2)} \quad (33)$$

Outer Film

$$\frac{dG_{If_o}}{dz} = (W_{D_o} - W_{E_o}) \frac{4(D_o - 2\delta_o)}{D_o^2 - D_i^2} \quad (34)$$

where W_D is the rate at which liquid initially carried in the core (presumably in the form of droplets) is deposited onto the film, per unit area of interface; and W_E is the rate at which liquid initially carried in the film (presumably as a continuous liquid phase) is entrained into the core, per unit area of interface. The entraining process is usually pictured as the breaking off of liquid droplets from the film due to the shearing action of the higher velocity core. The subscripts i and o refer, of course, to the inner and outer surfaces of the annulus.

The mass balance on the total liquid flow is

$$G_l = G_{If_i} + G_{lc} + G_{If_o} = \bar{G}(1 - \bar{X}) \quad (35)$$

3.2 NET INTERCHANGE RATE OF LIQUID DROPLETS BETWEEN CORE AND FILM

3.2.1 General

If a tube is long enough and effects of acceleration due to the pressure gradient are negligible, an adiabatic two-phase flow with moderate level of vapor weight fraction will become fully developed annular flow, in which the rate of deposition of liquid droplets matches the rate of entrainment from the film. Under these conditions, the amount of liquid entrained in the vapor core will remain constant with length and an equilibrium of liquid phase between the vapor core and the film will be set up. In other words, there exists an equilibrium phase distribution which depends only on values of local variables describing the fully-developed adiabatic two-phase flow system.

However, in a developing flow the entrainment and deposition rates are no longer balanced. Namely, these mass transfer processes interact in such a way that the system always tends towards its equilibrium state. If initially there is no liquid film on the solid wall in adiabatic two-phase flow, the deposition of the liquid droplets in the core onto the wall is the dominant process. On the other hand, if the system initially has a liquid film flow rate higher than the rate corresponding to the equilibrium state, entrainment of liquid film into the core is the dominant process. In a developing flow these two process rates are different from each other. Hence, liquid film measurements in a developing flow system should provide some information on the magnitude of these process rates which are not readily obtainable from a fully-developed flow system.

Figure 48. Annular Dispersed Flow in an Annulus.

Expressions for these processes are derived below.

It is intuitively obvious that deposition should be proportional to liquid droplet concentration in the core; the higher the axial droplet flux, the more droplets migrate transversely towards wall. As a first approximation, the deposition rate is assumed to be proportional to the droplet concentration in the core and to the turbulent intensity of the transverse velocity component. The deposition rate to the rod film is then written as

$$W_{D_i} \sim C_{\ell c} v' \quad (36)$$

The liquid concentration $C_{\ell c}$ and the velocity fluctuation v' may be expressed by

$$C_{\ell c} = \frac{G_{\ell c}}{U_{\ell c}} = \frac{G_{\ell c} S \rho_g}{G_g}$$

$$v' \sim \ell \left| \frac{dU}{dy} \right| = \sqrt{\frac{\tau_g}{\rho}}$$

where ℓ is the mixing length and y is the distance from the surface. Then the deposition rate at the film-core interface becomes,

$$W_{D_i} = \beta_i \frac{G_{\ell c} S \rho_g}{G_g} \sqrt{\frac{\tau_{c_i} g}{\rho_\ell}} \quad (37)$$

The entrainment rate is assumed to be proportional to the liquid concentration in the film and the transverse fluctuation velocity at film-core interface;

$$W_{E_i} \sim C_{\ell f} v'$$

For the purpose of evaluating $C_{\ell f}$ we further assume

$$U_{\ell f} = U_{\ell c}$$

Then

$$W_{E_i} = F_i \frac{G_{\ell f_i} S \rho_g}{G_g} \sqrt{\frac{\tau_{c_i} g}{\rho_\ell}} \quad (38)$$

Similarly, for the outer wall region,

$$W_{D_o} = \beta_o \frac{G_{\ell c} S \rho_g}{G_g} \sqrt{\frac{\tau_{c_o} g}{\rho_\ell}} \quad (39)$$

$$W_{E_o} = F_o \frac{G_{\ell f_o} S \rho_g}{G_g} \sqrt{\frac{\tau_{c_o} g}{\rho_\ell}} \quad (40)$$

The expressions for the entrainment given by Equation (38) and (40) are chosen as the simplest ones which satisfy the condition $W_E \rightarrow 0$ as $G_{lf} \rightarrow 0$. These equations allow entrainment from all finite film flows. This model is similar to one proposed by Biasi,¹³ but in contrast to one proposed by Moock¹¹ who specifies a threshold film flow below which there is no entrainment. Under equilibrium conditions, namely under fully developed conditions,

$$(W_{E_{eq}})_i = (W_{D_{eq}})_i$$

$$(W_{E_{eq}})_o = (W_{D_{eq}})_o$$

Hence, from Equations (37) and (38), we get the relation

$$\beta_i = F_i \frac{(G_{lf_{eq}})_i}{(G_{lc})_{eq}} \quad (41)$$

Similarly, from Equations (39) and (40), we get

$$\beta_o = F_o \frac{(G_{lf_{eq}})_o}{(G_{lc})_{eq}} \quad (42)$$

Substituting Equations (41) and (42) into (37) and (39), we can write:

$$W_{D_i} - W_{E_i} = F_i A_i S \left[\frac{(G_{lf_{eq}})_i}{(G_{lc})_{eq}} G_{lc} - G_{lf_i} \right] \quad (43)$$

$$W_{D_o} - W_{E_o} = F_o A_o S \left[\frac{(G_{lf_{eq}})_o}{(G_{lc})_{eq}} G_{lc} - G_{lf_o} \right] \quad (44)$$

where

$$A_i \equiv \frac{\rho_g}{G_g} \sqrt{\frac{\tau_{c_i} g}{\rho_l}} \quad \text{and} \quad A_o \equiv \frac{\rho_g}{G_g} \sqrt{\frac{\tau_{c_o} g}{\rho_l}}$$

As noted from Equations (43) and (44), the net interchange rates for both the outer and inner regimes are expressed in terms of both equilibrium and non-equilibrium parameters.

Let us write

$$I_i \equiv \frac{(G_{lf_{eq}})_i}{(G_{lc})_{eq}} G_{lc} - G_{lf_i} \quad (45)$$

$$I_o \equiv \frac{(G_{lf_{eq}})_o}{G_{lc_{eq}}} G_{lc} - G_{lf_o} \quad (46)$$

Noting that $G_l = G_{l_{eq}}$, it can be shown that

$$I_i = \frac{G_l}{G_{lc_{eq}}} \left[(G_{lf_{eq}})_i - G_{lf_i} \right] - \frac{(G_{lf_{eq}})_o}{G_{lc_{eq}}} \left[\frac{G_{lf_o}}{(G_{lf_{eq}})_o} (G_{lf_{eq}})_i - G_{lf_i} \right]$$

Rewriting Equation (45), one obtains

$$I_i = \left[1 - \frac{(G_{lf_{eq}})_o}{G_l} \right] \left(\frac{G_l}{G_{lc_{eq}}} \right) \left[(G_{lf_{eq}})_i - G_{lf_i} \right] + \epsilon_i \frac{(G_{lf_{eq}})_o}{G_l} \left(\frac{G_l}{G_{lc_{eq}}} \right) (G_{lf_{eq}})_i \quad (47)$$

where

$$\epsilon_i = 1 - \frac{G_{lf_o}}{(G_{lf_{eq}})_o}$$

Similarly for the outer wall, Equation (46) may be written

$$I_o = \left[1 - \frac{(G_{lf_{eq}})_i}{G_l} \right] \left(\frac{G_l}{G_{lc_{eq}}} \right) \left[(G_{lf_{eq}})_o - G_{lf_o} \right] + \epsilon_o \frac{(G_{lf_{eq}})_i}{G_l} \left(\frac{G_l}{G_{lc_{eq}}} \right) (G_{lf_{eq}})_o \quad (48)$$

where

$$\epsilon_o = 1 - \frac{G_{lf_i}}{(G_{lf_{eq}})_i}$$

Substituting Equations (47) and (48) into (43) and (44) respectively, the net deposition rates for the inner and outer films are given by

$$W_{D_i} - W_{E_i} = F_i A_i S I_i$$

$$= F_i A_i S \frac{G_l}{G_{lc_{eq}}} \left\{ \left[1 - \frac{(G_{lfeq})_o}{G_l} \right] \left[(G_{lfeq})_i - G_{lfi} \right] + \epsilon_i \frac{(G_{lfeq})_o}{G_l} (G_{lfeq})_i \right\} \quad (49)$$

$$W_{D_o} - W_{E_o} = F_o A_o S \frac{G_l}{G_{lc_{eq}}} \left\{ \left[1 - \frac{(G_{lfeq})_i}{G_l} \right] \left[(G_{lfeq})_o - G_{lfo} \right] + \epsilon_o \frac{(G_{lfeq})_i}{G_l} (G_{lfeq})_o \right\} \quad (50)$$

where

$$\epsilon_i = 1 - \frac{G_{lfo}}{(G_{lfeq})_o}$$

$$\epsilon_o = 1 - \frac{G_{lfi}}{(G_{lfeq})_i}$$

Equations 49 and 50 are coupled with each other through the terms ϵ_i and ϵ_o . Hence, solving the Equations 33 and 34 for the case in which both tube and rod films are developing, requires knowledge of coefficients F_i and F_o as well as fully-developed tube and rod film flow rates.

The method used in this study to obtain the expressions for the interchange rates is described below.

3.2.2 Rod Film Region

In solving Equation 33 for the rod film flow rate, it is assumed that ϵ_i is zero, namely, the tube film is in fully-developed condition. This decouples Equation 49 from 50, and Equation 49 is reduced to

$$W_{D_i} - W_{E_i} = F_i A_i S \frac{G_l}{G_{lc_{eq}}} \left[1 - \frac{(G_{lfeq})_o}{G_l} \right] \left[(G_{lfeq})_i - G_{lfi} \right] \quad (51)$$

A functional form of the term associated with the equilibrium parameters in Equation 51, i.e., $\left(\frac{G_l}{G_{lc_{eq}}} \right) [1 - (G_{lfeq})_o / G_l]$, was obtained by examining the term using the adiabatic liquid film model of Levy¹⁵.

This model suggests that

$$\left(\frac{G_l}{G_{lc_{eq}}} \right) \left[1 - \frac{(G_{lfeq})_o}{G_l} \right] \sim \frac{1}{\sqrt{GX}}$$

Hence, it is reasonable to assume that the net interchange rate of Equation 51 has functional dependence on the system variables of the form

$$W_{D_i} - W_{E_i} = F \left(G, X, \alpha, \frac{\rho_l}{\rho_g} \right) \cdot A_{eq_i} \cdot \left((G_{lf_{eq}})_i - G_{lf_i} \right) \quad (52)$$

where

$$A_{eq_i} = \frac{\rho_g}{G_g} \sqrt{\frac{(\tau_{ceq})_i^g}{\rho_l}}$$

The correct functional form of F was established by analyzing the developing adiabatic rod film flow data of Moeck¹¹. The analysis yielded the following expression which best fits the data:

$$F = 0.0164 \frac{X^{1.19}}{(G/10^6)^{0.4}} \left(\frac{\rho_l}{\rho_g} \right)^{1.2} \quad (53)$$

3.2.3 Tube Film region

Assuming $\beta_o = K_1 \beta_i$, it can be shown from Equations 37, 38, 39 and 40 that

$$F_o = K_1 F_i \frac{(G_{lf_{eq}})_i}{(G_{lf_{eq}})_o} \quad (54)$$

Substituting Equation 54 and the following approximation

$$\sqrt{\frac{\tau_{co}}{\tau_{ci}}} = K_2 \sqrt{\frac{(\tau_{ceq})_o}{(\tau_{ceq})_i}}$$

into Equation 50 and rearranging, the net interchange rate in the tube film region can be written as follows:

$$W_{D_o} - W_{E_o} = K_1 K_2 F A_{eq_o} \frac{(G_{lf_{eq}})_i}{(G_{lf_{eq}})_o} \left[\left(\frac{G_l - (G_{lf_{eq}})_i}{G_l - (G_{lf_{eq}})_o} \right) \left((G_{lf_{eq}})_o - G_{lf_o} \right) \right. \\ \left. + \left(\frac{(G_{lf_{eq}})_i - G_{lf_i}}{G_l - (G_{lf_{eq}})_o} \right) (G_{lf_{eq}})_o \right] \quad (55)$$

where

$$A_{eq_o} = \frac{\rho_g}{G_g} \sqrt{\frac{(r_{ceq})_o^g}{\rho_l}}$$

The coefficient $K_1 K_2$ was established by analyzing the developing, adiabatic tube film flow data of Moeck.¹¹ $K_1 K_2 = 0.915$ was chosen as the value best fitting the data.

3.3 METHOD FOR FILM GROWTH CALCULATION

The following is a summary of the Equations to be solved for G_{lf_i} and G_{lf_o} :

Rod Film:

$$\frac{dG_{lf_i}}{dZ} = F A_{eq_i} g_i \left[(G_{lf_{eq}})_i - G_{lf_i} \right] \quad (33)$$

Tube Film:

$$\frac{dG_{lf_o}}{dZ} = 0.915 F A_{eq_o} g_o \left(\frac{(G_{lf_{eq}})_i}{(G_{lf_{eq}})_o} \right) \left\{ \left(\frac{G_l - (G_{lf_{eq}})_i}{G_l - (G_{lf_{eq}})_o} \right) \left((G_{lf_{eq}})_o - G_{lf_o} \right) + \left(\frac{(G_{lf_{eq}})_i - G_{lf_i}}{G_l - (G_{lf_{eq}})_o} \right) (G_{lf_{eq}})_o \right\} \quad (34)$$

Where

$$F = 0.0164 \frac{X^{1.19}}{(G/10^6)^{0.4}} \left(\frac{\rho_l}{\rho_g} \right)^{1.2} \quad (53)$$

$$A_{eq_i} = \frac{\rho_g}{G_g} \sqrt{\frac{(r_{ceq})_i^g}{\rho_l}}$$

$$A_{eq_o} = \frac{\rho_g}{G_g} \sqrt{\frac{(r_{ceq})_o^g}{\rho_l}}$$

$$g_i = \frac{4 (D_i + 2 \delta_i)}{D_o^2 - D_i^2}$$

$$g_o = \frac{4 (D_o - 2 \delta_o)}{D_o^2 - D_i^2}$$

The interfacial shears next to the rod and tube wall were calculated from the following equations. These were derived assuming that the density head in the core, and the film thicknesses δ_o and δ_i , are negligible:

$$(\tau_{ceq})_i = \frac{D_i}{4} \left[\left(\frac{2S}{D_i} \right)^2 - 1 \right] \left(-\frac{dp}{dz} \right) \quad (56)$$

$$(\tau_{ceq})_o = \frac{D_o}{4} \left[1 - \left(\frac{2S}{D_o} \right)^2 \right] \left(-\frac{dp}{dz} \right) \quad (57)$$

where S is the radius of zero shear, given by Leung, et al¹⁶ as

$$S = \left[\left(\frac{D_i}{D_o} \right)^{0.343} D_o + D_i \right] / 2 \left[1.0 + \left(\frac{D_o}{D_i} \right)^{0.343} \right] \quad (58)$$

The pressure gradient was evaluated from

$$\frac{dp}{dz} = \left(\frac{dp}{dz} \right)_H + \left(\frac{dp}{dz} \right)_F \quad (59)$$

where

$$\left(\frac{dp}{dz} \right)_H = \rho_l (1 - \alpha) + \rho_g \alpha$$

$$\left(\frac{dp}{dz} \right)_F = \frac{G^2}{2g_c \rho_l} \frac{f}{D_h} \phi_{Lo}^2$$

The Martinelli two-phase friction multiplier⁹ and the Zuber-Findlay void fraction correlation¹⁷ were used in the present analysis.

To calculate the rod and tube film flow rates, G_{lf_i} and G_{lf_o} at $Z = 0$, and $(G_{lf_{eq}})_i$ and $(G_{lf_{eq}})_o$ are required. These were obtained from the test data of Moeck,¹¹ and listed in Table 8. In performing the integration of 33 and 34, δ_i and δ_o were assumed negligible.

Note that the tube film flow calculation with Equation 34 requires values of the developing rod film flow G_{lf_i} . Hence G_{lf_o} was determined by solving Equations 33 and 34 simultaneously.

3.4 COMPARISON OF MODEL WITH EXPERIMENTAL RESULTS

Moeck¹¹ reported measurements of adiabatic developing liquid film flows on the rod and tube walls of a concentric vertical annulus (0.776 inch inner (rod) diameter and 0.936 inch outer (tube) diameter). The working fluid was steam-water at 500 and 1000 psia. The rod was segmented, consisting of an unheated entrance length, an electrically heated length, and an unheated deposition length which terminated in a porous insert. Various unheated deposition lengths were used for the rod film flow measurements. Another porous insert was mounted in the unheated outer (tube) wall. The exit end of the heated length (corresponds to the inlet end of the deposition length) was maintained at a dryout condition while the rod and tube film flows were measured. The test results provided a comprehensive picture of both rod and tube film growth behaviour as well as the corresponding fully-developed rod and tube film flows. The rod and tube film data of Moeck¹¹ considered in the present study are summarized in Table 8.

Table 8
SUMMARY OF ROD AND TUBE FILM DATA OF MOECK¹¹

Run No.	Pressure (Psig)	$\bar{G} \times 10^{-6}$ (lb/hr-ft) ²	X_o	Z/D_h	Rod Film			Z/D_h	Tube Film	
					$(W_{\ell f_i})^{**}$ (lb/hr) ^{eq}	$W_{\ell f_i}$ (lb/hr)	$G_{\ell f_i}/G_{\ell}$		$W_{\ell f_o}$ (lb/sec)	$G_{\ell f_o}/G_{\ell}$
-	1000	1.000	0.280	0	-	31.2	0.0290 [†]	0	700	0.654 ^{††}
704	1000	1.002	0.294	-	-	-	-	44	651	0.616
705	998	1.003	0.255	-	-	-	-	44	700	0.627
454	1007	1.006	0.293	34	152	47	0.0442	55	630	0.593
455	1003	1.001	0.204	34	175	55	0.0500	56	700	0.636
505	1005	1.008	0.281	78	160	82	0.0757	107	595	0.550
554	998	1.000	0.286	157	159	135	0.1266	178	561	0.526
555	1000	0.993	0.282	157	164	118	0.1108	178	570	0.535
604	999	1.005	0.273	308	167	160	0.1465	329	512	0.470
209	994	0.977	0.276	715	170	170	0.1607	736	414*	0.392
201	1000	0.984	0.284	715	164*	164	0.1558	736	430	0.409
-	1000	1.000	0.380	0	-	16.9	0.0183 [†]	0	470	0.507 ^{††}
706	997	0.979	0.378	-	-	-	-	44	431	0.474
501	1000	0.976	0.381	78	98	47	0.0520	107	380	0.421
551	1002	0.974	0.381	157	98	78	0.0866	178	325	0.361
601	996	0.980	0.376	308	100	94	0.1028	329	236	0.258
607	999	0.977	0.380	308	98*	93	0.1027	329	231	0.255
-	1000	1.000	0.480	0	-	7.890	0.0101 [†]	0	150	0.193 ^{††}
703	1000	0.981	0.475	-	-	-	-	44	130	0.169
453	1003	0.973	0.466	34	52	21	0.0270	55	156	0.201
503	1004	0.977	0.477	78	47	26	0.0340	107	143	0.188
553	1000	0.981	0.476	157	47	41	0.0634	178	128	0.167
603	998	0.978	0.477	308	47*	44	0.0575	329	113	0.148
-	1000	1.000	0.670	0	-	1.080	0.0020 [†]	0	-	-
450	996	0.978	0.677	34	14	2	0.0042	55	34	0.072
500	1002	0.979	0.671	78	14	8	0.0166	107	37	0.077
550	1005	0.970	0.681	157	14	15	0.0324	178	31	0.067
600	1001	0.974	0.675	308	14	14	0.0296	329	30	0.063
-	1000	2.300	0.280	0	-	0	0 [†]	0	297	0.120 ^{††}
701	997	2.310	0.280	-	-	-	-	44	211	0.085
451	997	2.460	0.278	34	21	2	0.0008	55	302	0.114
552	1004	2.333	0.282	157	23	20	0.0080	178	211	0.084
602	997	2.332	0.282	308	23	23	0.0092	329	176	0.070
200	999	1.987	0.291	715	32*	32	0.0152	736	145*	0.069

Table 8 (Continued)

Run No.	Pressure (Psig)	$\bar{G} \times 10^6$ (lb/hr-ft) ²	X_o	Z/D_h	Rod Film			Tube Film		
					$(W_{\ell f_i})^{**}$ $G_{\ell f_i}$ eq (lb/hr)	$W_{\ell f_i}$ (lb/hr)	$G_{\ell f_i}$ G_ℓ	Z/D_h	$W_{\ell f_o}$ (lb/sec)	$G_{\ell f_o}$ G_ℓ
-	500	1.000	0.320	0	-	20	0.0200 [†]	0	650	0.640 ^{††}
710	507	0.994	0.304	-	-	-	-	44	548	0.530
460	510	1.005	0.302	34	95	49	0.0467	55	565	0.539
514	508	1.001	0.328	78	74	60	0.0597	107	412	0.410
564	502	0.996	0.316	157	85	80	0.0785	178	364	0.358
614	507	1.010	0.311	308	86*	88	0.0846	329	248	0.238
216	497	0.977	0.279	715	121	117	0.1102	736	232*	0.220
-	500	1.000	0.390	0	-	7.250	0.0080 [†]	0	346	0.380 ^{††}
712	500	0.973	0.385	-	-	-	-	44	265	0.296
462	501	0.980	0.387	34	51	22	0.0245	55	310	0.345
512	501	0.980	0.394	78	49	36	0.0405	107	222	0.250
562	502	0.988	0.385	157	51	45	0.0496	178	168	0.185
612	512	0.982	0.390	308	50*	47	0.0525	329	125	0.140
213	499	0.973	0.385	715	52	48	0.0537	736	93*	0.104
-	500	1.000	0.590	0	-	0	0 [†]	0	-	-
464	506	0.973	0.577	34	17	1	0.0016	55	35	0.057
510	507	0.983	0.585	78	16	9	0.0146	107	36	0.059
560	511	0.977	0.586	157	16	16	0.0264	178	29	0.048
610	499	0.968	0.583	308	17*	15	0.0249	329	31	0.051
210	498	0.976	0.593	715	16	19	0.0320	736	38	0.064
-	500	1.470	0.290	0	-	27.3	0.0175 [†]	0	740	0.475 ^{††}
463	509	1.482	0.280	34	44	33	0.0207	55	576	0.361
513	511	1.474	0.295	78	39	38	0.0245	107	420	0.271
563	510	1.473	0.287	157	42	42	0.0281	178	336	0.215
613	500	1.483	0.289	308	40	40	0.0254	329	182	0.115
212	497	1.468	0.291	715	41*	41	0.0264	736	85*	0.055

† Estimated value obtained from Figures B.21, B.22 and 8.9 of Ref. 11.

†† Estimated value obtained from special plots of $G_{\ell f_o}/G_\ell$ vs. Z/D_h .

* Equilibrium value used for the present model for prediction of the developing film.

** Smoothed values from Figure 8.16 of Ref. 11.

Figures 49 and 50 show the fully-developed rod and tube film flow data respectively, taken at $G = 1 \times 10^6$ lb/h ft² for $p = 500$ and 1000 psia. It can be seen that both $(G_{\ell f_{eq i}})$ and $(G_{\ell f_{eq o}})$ increase with pressure, but vary inversely with steam quality. At any given quality, the value $(G_{\ell f_{eq o}})$ is approximately 2 to 3 times the value of $(G_{\ell f_{eq i}})$.

Developing rod film behavior is illustrated in Figures 51 and 52, in which $G_{\ell f_i}/G_{\ell}$ is plotted as a function of Z/D_h , with steam quality as parameter. The Moeck results indicate that CHF conditions at the end of the heated rod did not always coincide with zero rod film flow. As shown in the figures, the measured rod film flow at the CHF location was sometimes an appreciable fraction of the adiabatic fully developed film. These figures show that at fixed quality, the rod film grows rapidly at first and then tends asymptotically to $(G_{\ell f_{eq i}})$ at large Z .

The developing tube film data are plotted in Figures 53 and 54, in the form of $G_{\ell f_o}/G_{\ell}$ v.s. Z/D_h with X as parameter. These figures show that the tube film flow at $Z = 0$ and 1000 psia is as much as twice the fully developed value at the same G and X , and at 500 psia is as much as six or seven times the fully developed value at the same G and X . It is evident from this that heating one wall of an annulus produces a significantly higher film flow rate on the other wall. Except at high X , entrainment depletes the tube film as it moves along the channel, and the tube film flow rate approaches asymptotically its equilibrium value $(G_{\ell f_{eq o}})$ at large Z .

Calculations of developing film flow on both rod and tube were carried out for the same conditions as Moeck's test runs. The equilibrium values used in the calculations are the same as plotted in Figures 49 and 50. The rod initial values are the values obtained by extrapolation to $Z = 0$ in Figures B.21, B.22, and 8.9 of Moeck's thesis¹¹. The tube initial values were obtained by extrapolation to $Z = 0$ on special plots of $G_{\ell f_o}/G_{\ell}$ vs. Z/D_h prepared for this purpose. The initial and equilibrium values are given in Table 8.

The model described in the preceding section which is the basis for the calculations may be evaluated by comparing predicted with measured values of film flow rate. Figure 55 is a plot of $W_{\ell f_i} - (W_{\ell f_i})_c$ vs. Z/D_h . Eighty % of the calculated values are within the average of the uncertainties (95% confidence) for the measured rod film flow rates as reported by Moeck.¹¹ Alternately, the difference $W_{\ell f_i} - (W_{\ell f_i})_c$ may be expressed as a percentage of $W_{\ell f_i}$. On this basis, 85% of the calculated values are within $\pm 15\%$ of the measured.

Figure 56 is a plot of $W_{\ell f_o} - (W_{\ell f_o})_c$ vs. Z/D_h . In this case 56% of the calculated values are within the average of the uncertainty. However, 80% of the calculated values are within $\pm 15\%$ of measured.

The model does a good job of predicting film flow rate, provided the initial and equilibrium values are known. Errors in the predicted values are of the same order as uncertainties in measurement.

The model prediction has been superposed on Figures 51, 52, 53, and 54. Referring again to these figures, the model predicts very well the salient trends in the data, (e.g., steep initial gradient, asymptotic approach to equilibrium) as well as the absolute values of the points themselves. Note that the initial rod film flow rate (value at $Z = 0$) is generally not zero. During many of Moeck's test runs a CHF condition was being sensed by only one or two thermocouples at the exit end of the heated rod. There were other exit thermocouples at other circumferential positions which sensed no incipient CHF. The film still continued to flow in these other sectors. The average film flow rate for these runs was therefore not zero at $Z = 0$. This fact is reflected in the generally non-zero initial values for $G_{\ell f_i}$.

Dependence of the rod film growth rate on the system variables was examined by plotting the calculated results in a non-dimensional form, $\Delta G_{\ell f_i} / (\Delta G_{\ell f_i})_{Z=0}$ v.s. Z/D_h where

$$\Delta G_{\ell f_i} = (G_{\ell f_{eq i}})_i - G_{\ell f_i}$$

This form was suggested by solution of Equation 33, i.e.,

$$\frac{\Delta G_{\ell f_i}}{[\Delta G_{\ell f_i}]_{Z=0}} = \text{Exp}(-g_i F A_{eq i}) Z \quad (60)$$

Figure 49. Fully Developed Liquid Film Flow on Inner (Rod) Surface of Annulus.

Figure 50. Fully Developed Liquid Film Flow on Outer (Tube) Surface of Annulus.

Figure 51A. Developing Film on Rod, $P = 1000 \text{ psia}$, $G = 1 \times 10^6 \text{ lb/h-ft}^2$.

Figure 51B. Developing Film on Rod, $P = 1000 \text{ psia}$, $G = 2.3 \times 10^6 \text{ lb/h-ft}^2$.

Figure 52A. Developing Film on Rod, $P = 500 \text{ psia}$, $G = 1 \times 10^6 \text{ lb/h-ft}^2$.

Figure 52B. Developing Film on Rod, $P = 500 \text{ psia}$, $G = 1.47E6$

Figure 53A. Developing Film on Tube, $P = 1000 \text{ psia}$, $G = 1 \times 10^6 \text{ lb/h-ft}^2$.

Figure 53B. Developing Film on Tube, $P = 1000$ psia, $G = 2.3 \times 10^6$ lb/h-ft².

Figure 54A. Developing Film on Tube, $P = 500 \text{ psia}$, $G = 1 \times 10^6 \text{ lb/h.-ft}^2$.

Figure 54B. Developing Film on Tube; $P = 500 \text{ psia}$, $G = 1.47E6$

Figure 55. Measured Minus Calculated Rod Film Flow Rate versus Adiabatic Length

Figure 56. Measured Minus Calculated Tube Film Flow Rate versus Adiabatic Length

Calculated rod film flows for $G = 1 \times 10^6$ lb/h-ft² at 1000 and 500 psia were plotted in Figures 57 and 58, with steam quality as parameter. It should be noted that the steeper the slope, the shorter the developing distance $(Z/D_h)_{FD}$. The results indicate that the $(Z/D_h)_{FD}$ decreases with increasing steam quality. In Figure 59 the rod film flows for $X = 0.38$ and $G = 1 \times 10^6$ lb/h-ft² at two different pressures 500 and 1000 psia are compared to show pressure effect; $(Z/D_h)_{FD}$ decreases with decreasing pressure. Rod film flows for $X = 0.28$ and $p = 1000$ psia, at the two different mass velocities 1.0 and 2.0×10^6 lb/h-ft², are compared in Figure 60 to show the effect of mass velocity. The results show that $(Z/D_h)_{FD}$ decreases with decreasing mass velocity.

The effects of the various system variables given by the model are in general agreement with the experimental data of Moeck.

Figure 57. $\Delta G_{L_i}/[\Delta G_{L_i}]_{z=0}$ versus z/D_h , $P = 1000 \text{ psia}$, $G = 1 \times 10^6 \text{ lb/h-ft}^2$.

Figure 58. $\Delta G_{gf} / (\Delta G_{gf})_{z=0}$ versus z/D_h , $P = 500 \text{ psia}$, $G = 1 \times 10^6 \text{ lb/h-ft}^2$.

Figure 59. $\Delta G_{2f_i} / (\Delta G_{2f_i})_{z=0}$ versus z/D_h , $G = 1 \times 10^6$ lb/h-ft², $X = 0.38$.

Figure 60. $\Delta G_{2f_i} / (\Delta G_{2f_i})_{z=0}$ versus z/D_h , $P = 1000$ psia, $X = 0.28$.

4. CONCLUSIONS, PART II

A simplified description of film mean velocity, with allowance for some void in the film, appears adequate for calculating flow rate within the film as well as the film flow rate, provided the film is fully developed.

The non-dimensional velocity and void profiles in the film assumed in this analysis yield a unique film flow rate – film thickness relationship $G_{\ell f}^+$ vs. $y + (y + \leq \delta +)$ which is exhibited by the data of both Part I and CISE.¹² For any fully developed flow, then, given the film thickness, the film liquid flow rate can be predicted from this relationship.

The diabatic film data do not follow exactly the $G_{\ell f}^+$ vs $y +$ relationship for fully developed flow. Instead, they exhibit effects of the specific system variables flow, quality, and heat flux. However, it was found that the diabatic data of Part I could be correlated with the adiabatic data by means of the simple functional relationships.

$$\frac{(G_{\ell f}^+)_d}{(G_{\ell f}^+)_a} = 1 - 3\left(\frac{\phi}{10^6}\right)\left(\frac{\bar{G}}{10^6}\right) \bar{x}$$

There may also be effects of other parameters, such as pressure, geometry, etc. The present data are not sufficient to examine these latter effects.

The liquid droplet interchange model derived in this study is able to predict the correct trends in variation of developing adiabatic rod and tube film flows with various system variables. Both the analysis and the annulus data indicate that the higher the mass flow and pressure and the lower the quality, the longer the developing length will be. However, the effect of quality is in contrast with the one indicated by the circular tube data reported in Part 1. Comparison between the predictions and measurements of developing rod and the tube film flow rates indicate that 80 to 85% of the predicted values are within $\pm 15\%$ of the measurements.

According to the model, the developing liquid film grows or depletes in proportion to departure from its fully developed state $(G_{\ell f_{eq}} - G_{\ell f})$. This description of the interchange process appears to be the logical one because it provides a clear asymptote $(G_{\ell f_{eq}})$ to which the developing film must tend as distance increases. The major limitation of

the model is however, that the value of $G_{\ell f_{eq}}$ must be known to perform calculations of film growth rate.

The analytical approach employed in the present study may be extended to formulate a CHF model which predicts the "dryout" point at which boiling heat transfer in the annular regime breaks down.

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NOMENCLATURE

A	Area, ft ²
C	Coefficient
c_p	Specific heat, Btu/lb-°F
D	Diameter, ft
D_h	Hydraulic diameter, ft
f	Pipe friction factor
G	Mass velocity, lb/h-ft ²
g	Gravitational constant, 32.174 ft/sec ²
h	Heat transfer coefficient, Btu/h-ft ² -°F
h	Head, ft
h'	Manometer deflection, in.
h_{fg}	Latent heat of vaporization, Btu/lb
Δh_s	Subcooling, Btu/lb
K	Coefficient
L	Length, ft
L_u	Unheated length, i.e., distance between exit end of heated length and exit end of channel, ft.
N_R	Reynolds number
P, p	Pressure, psia
ΔP	Pressure drop, lb/ft ² or lb/in ² .
q_L	Heat loss, Btu/hr
R	Inside radius of circular tube test section, ft.
r	Radius, ft
S	Slip ratio U_g/U_l
T	Temperature, °F

U	Velocity, ft/sec
U^+	Nondimensional velocity U/V^* .
V^*	Shear velocity $\bar{U} (f/8)^{1/2} = (\tau_w g / \rho_Q)^{1/2}$, ft/sec.
ν'	Turbulent intensity for transverse velocity component, ft/sec.
$\dot{W}$	Mass flow rate, lb/sec.
W_D	Liquid droplet deposition rate, lb/h-ft ²
W_E	Liquid film entrainment rate, lb/h-ft ² .
X	Quality
y	Distance from wall, ft. or in.
y^+	Nondimensional distance from wall $y V^* / \nu_Q$
z	Vertical coordinate, hence axial coordinate for vertical channel, positive upward, ft.
α	Void fraction
Δ	Distance from wall to splitter, in.
δ	Film thickness, ft. or in.
δ^+	Nondimensional film thickness $\delta V^* / \nu_Q$
μ	Molecular viscosity, lb/h-ft ²
ν	Kinematic viscosity, ft ² • /sec
τ_c	Shear stress at film/core interface, lb/ft ²
τ_w	Wall shear stress, lb/ft ²
ρ	Density, lb/ft ³ .
ϕ	Heat flux, Btu/h-ft ² .

Subscripts

c	Calorimeter
c	Centerline
c	Cold water
c+s	Mixture
c	Core
eq	Equilibrium
F	Friction
f	Film
g	Vapor, or gas
H	Hydrostatic
i	Inner (rod)
l	Liquid
lc	Liquid in the core
lf	Liquid in the film
O	Orifice
o	Outer (tube)
r	Room
s	Sample
T	Test section
w	Wall
2ϕ	Two-phase
1	Test section inlet, or first pressure tap
2	Test section exit, or second pressure tap
3, 4, --- 8	Third, fourth, etc., pressure taps
75	At 75°F

APPENDIX A

UNCERTAINTY ANALYSIS

The average channel quality at the exit end of the test channel is given by Equation A-1,

$$\bar{X} = \frac{1}{h_{fg}} \left[\frac{3413 \cdot \text{kilowatts} - q_{LT}}{3600 \dot{W}} - \Delta h_s \right] \quad (A-1)$$

The expression for the uncertainty interval by the method of Kline and McClintock¹⁸ is:

$$\delta \bar{X} = \frac{1}{\dot{W} h_{fg}} \left[\left\{ 0.948 (KW) \right\}^2 \left\{ \frac{\delta (KW)}{(KW)} \right\}^2 + \left\{ 0.948 (KW) - q_{LT} \right\}^2 \left\{ \frac{\delta \dot{W}}{\dot{W}} \right\}^2 + \left(\delta q_{LT} \right)^2 + \dot{W}^2 \left(\delta \Delta h_s \right)^2 + \left(\dot{W} \bar{X} \right)^2 \left(\delta h_{fg} \right)^2 \right]^{1/2} \quad (A-2)$$

where

$$\left\{ \frac{\delta (KW)}{(KW)} \right\} = 0.01^*$$

$$\left\{ \frac{\delta \dot{W}}{\dot{W}} \right\} = 0.02^*$$

$$(\delta q_{LT}) = 0.948 \text{ Btu/sec}$$

$$(\delta \Delta h_s)^2 = (\delta h_f)^2 + (\delta h_1)^2$$

$$= \left(\frac{\partial h_f}{\partial P} \right)_{P=1000}^2 (\delta P)^2 + \bar{C}^2 (\delta T_1)^2$$

$$= (0.154)^2 (10^*)^2 + 1 (5^*)^2 = 27.37$$

$$(\delta h_{fg})^2 = \left(\frac{\partial h_{fg}}{\partial P} \right)_{P=1000}^2 (\delta P)^2$$

$$= (-0.192)^2 (10^*)^2 = 3.68$$

*These numbers are the "estimated error limits" given earlier. They may be thought of as "95% confidence limits."

Substituting in Equation A-2,

$$\delta \bar{X} = \frac{1}{650.4 \dot{W}} \left[\left\{ \frac{0.948 (KW)}{100} \right\}^2 + \left\{ \frac{0.948 (KW) - 1.94}{50} \right\}^2 + 0.898 + 27.37 \dot{W}^2 + 3.68 (\dot{W} \bar{X})^2 \right]^{1/2} \quad (A-3)$$

Similarly, the expression for the uncertainty interval in the sample flow is:

$$\delta \left(\frac{\dot{W}_s}{\dot{W}} \right) = \left(\frac{\dot{W}_s}{\dot{W}} \right) \left[\left(\frac{\dot{W}_{c+s}}{\dot{W}_s} \right)^2 \left(\frac{\delta \dot{W}_{c+s}}{\dot{W}_{c+s}} \right)^2 + \left(\frac{\dot{W}_c}{\dot{W}_s} \right)^2 \left(\frac{\delta \dot{W}_c}{\dot{W}_c} \right)^2 + \left(\frac{\delta \dot{W}}{\dot{W}} \right)^2 \right]^{1/2} \quad (A-4)$$

where

$$\left(\frac{\delta \dot{W}_{c+s}}{\dot{W}_{c+s}} \right) = 0.02^*$$

$$\left(\frac{\delta \dot{W}_c}{\dot{W}_c} \right) = 0.02^*$$

Substituting in Equation A-4,

$$\delta \left(\frac{\dot{W}_s}{\dot{W}} \right) = \frac{1}{50} \frac{\dot{W}_s}{\dot{W}} \left[\left(\frac{\dot{W}_{c+s}}{\dot{W}_s} \right)^2 + \left(\frac{\dot{W}_c}{\dot{W}_s} \right)^2 + 1 \right]^{1/2} \quad (A-5)$$

Finally, the expression for the uncertainty interval in the sample quality is:

$$\begin{aligned} \delta X_s = \frac{1}{\dot{W}_s h_{fg}} & \left[\left\{ (h_{c+s})^2 + (h_{fg} X_s + h_f)^2 \right\} (\dot{W}_{c+s})^2 \left\{ \frac{\delta \dot{W}_{c+s}}{\dot{W}_{c+s}} \right\}^2 \right. \\ & + \left\{ (h_c)^2 + (h_{fg} X_s + h_f)^2 \right\} (\dot{W}_c)^2 \left\{ \frac{\delta \dot{W}_c}{\dot{W}_c} \right\}^2 + (\dot{W}_{c+s})^2 (\delta h_{c+s})^2 \\ & + (\dot{W}_c)^2 (\delta h_c)^2 + (\dot{W}_s)^2 (\delta h_f)^2 + (\dot{W}_s X_s)^2 (\delta h_{fg})^2 \\ & \left. + (\delta q_{LC})^2 \right]^{1/2} \quad (A-6) \end{aligned}$$

*These numbers are the "estimated error limits" given earlier. They may be thought of as "95% confidence limits."

b

where

$$(\delta h_{c+s}) = \bar{C} (\delta T_{c+s}) = 0.005 * \bar{C} (T_{c+s} - 150)$$

$$= \frac{T_{c+s} - 150}{200}$$

$$(\delta h_c) = \frac{T_c - 150}{200}$$

$$(\delta h_f)^2 = 2.37$$

$$(\delta q_{LC})^2 = 0.043$$

Substituting in Equation A-6

$$\begin{aligned} \delta X_s = \frac{1}{650.4 \dot{W}_s} & \left[\left\{ \left(\frac{h_{c+s}}{50} \right)^2 + (13.01 X_s + 10.85)^2 + \left(\frac{T_{c+s} - 150}{200} \right)^2 \right\} (\dot{W}_{c+s})^2 \right. \\ & + \left\{ \left(\frac{h_c}{50} \right)^2 + (13.01 X_s + 10.85)^2 + \left(\frac{T_c - 150}{200} \right)^2 \right\} (\dot{W}_c)^2 \\ & \left. + 2.37 (\dot{W}_s)^2 + 3.68 (\dot{W}_s X_s)^2 + 0.043 \right]^{1/2} \end{aligned} \quad (A-7)$$

The uncertainty intervals in $\bar{X}$, $\dot{W}_s/\dot{W}$, and X_s have been calculated by the procedure outlined above, for several typical runs. The results are given in Table A-1 and also indicated in Figures 13, 14, 16, 17, 25, 26, 27.

*These numbers are the "estimated error limits" given earlier. They may be thought of as "95% confidence limits."

Table A-1

Run No.	$\dot{W}$	(KW)	$\bar{X}$	$\frac{\dot{W}_s}{\dot{W}}$	$\dot{W}_s$	$\dot{W}_{c+s}$	$\dot{W}_c$	h_{c+s}	X_s	T_{c+s}	h_c	T_c	$\delta \bar{X}$	$\delta \left(\frac{\dot{W}_s}{\dot{W}} \right)$	δX_s
1016	0.718	210	0.099	0.0885	0.0635	0.0850	0.0215	414.6	0.0116	436	41	73	0.0129	0.0030	0.0296
1021	0.716	234	0.218	0.0821	0.0587	0.0762	0.0175	441.5	0.0447	460	42	74	0.0135	0.0027	0.0301
1054	0.715	207	0.311	0.0953	0.0682	0.0880	0.0198	439.3	0.0171	458	71	103	0.0125	0.0032	0.0291
1055	0.718	239	0.370	0.1062	0.0762	0.0994	0.0232	450.7	0.0460	468	71	103	0.0136	0.0035	0.0303
1072	0.717	209.5	0.2099	0.0869	0.0623	0.0765	0.0142	456.3	0.0214	473	62	94	0.0126	0.0028	0.0282
1078	1.087	210	0.1445	0.0677	0.0736	0.0879	0.0143	471.5	0.0317	486	44	76	0.0103	0.0021	0.0278
1079	0.360	210	0.4044	0.0886	0.0319	0.0427	0.0108	423.5	0.0425	444	44	76	0.0209	0.0030	0.0317
1080	0.357	210.5	0.1517	0.0835	0.0298	0.0400	0.0102	423.5	0.0479	444	46	78	0.0211	0.0029	0.0321
1082	0.355	212	0.3550	0.0948	0.0336	0.0436	0.0100	446.1	0.0626	464	48	80	0.0213	0.0032	0.0315
1084	0.359	127	0.1684	0.0699	0.0251	0.0349	0.0098	410.1	0.0465	432	49	81	0.0145	0.0025	0.0336
1088	0.714	109.5	0.1091	0.0746	0.0533	0.0681	0.0148	417.9	0.0108	439	39	71	0.0097	0.0025	0.0284
1099	0.367	103.5	0.2356	0.1269	0.0465	0.0614	0.0149	410.1	0.0014	432	42	74	0.0128	0.0043	0.0292
1100	0.367	118.5	0.2893	0.1267	0.0465	0.0610	0.0145	428.0	0.0296	448	40	72	0.0137	0.0043	0.0300
2006	0.718	234	0.1900	0.1369	0.0983	0.1211	0.0228	462.2	0.0369	478	41	73	0.0134	0.0044	0.0284
2008	0.715	232	0.0640	0.1008	0.0721	0.0949	0.0228	433.5	0.0369	453	40	72	0.0134	0.0034	0.0300
2034	0.720	139	0.1878	0.1805	0.1299	0.1547	0.0248	463.4	0.0102	479	41	73	0.0104	0.0057	0.0269
3009	0.724	282	0.288	0.2164	0.1565	0.1893	0.0328	455	0.0963	472	49	78	0.0151	0.0068	0.0288
3016	0.716	236	0.113	0.1969	0.1410	0.1980	0.0570	415.7	0.0378	437	50	82	0.0135	0.0070	0.0315
3021	1.078	240	0.104	0.1660	0.1789	0.2209	0.0420	468.0	0.0436	483	41	73	0.0109	0.0053	0.0287

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