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**TWO-PHASE FLOW
AND HEAT TRANSFER
IN MULTIROD GEOMETRIES
TWELFTH
QUARTERLY PROGRESS REPORT
JULY 1 - SEPTEMBER 30, 1968**

US ATOMIC ENERGY COMMISSION
CONTRACT AT(04-3)-189
PROJECT AGREEMENT 44

ATOMIC POWER EQUIPMENT DEPARTMENT
GENERAL ELECTRIC
SAN JOSE, CALIFORNIA

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TWO-PHASE FLOW AND HEAT TRANSFER IN MULTIROD GEOMETRIES

TWELFTH QUARTERLY PROGRESS REPORT

July 1 - September 30, 1968

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SUMMARY

Task A

Entrainment Fraction in Fully-Developed
Annular Dispersed Two-Phase Flow

Much entrainment fraction data from adiabatic annular dispersed two-phase flows have been examined. Using the entrainment fraction independent variable of Paleev and Fillipovich, one is able to account for area, density, surface tension, and flow rate effects for fully-developed flows. The data of Steen, taken with several fluids covering an extensive range of liquid viscosities, indicate that the Paleev and Fillipovich variable does not properly account for the liquid viscosity. Based on Steen's silicone data, a modified Paleev and Fillipovich variable that properly accounts for the liquid viscosity is presented. Also presented is the resulting correlation of the data of Steen, Minh and Huyghe, and Alia, et al., with this variable.

Linear Air Velocity Profiles

The air linear velocity profiles from the present investigation of annular-dispersed round tube data are found to agree with the results of Alia, et al., in terms of $(U_G - U)/U_T$ versus y/R . These profiles, for flow qualities greater than 11%, lie between the single-phase pipe and flat-plate correlations.

Task C

Low-Pressure Channel

The low-pressure air-water test channel to study film thickness and flow rate measurements is described. Film flow rate and thickness measurements of a zero void film (no roll waves) are reported to be in agreement with the zero void model of Levy. There is good agreement of the air velocity profile data with the data reported in Task A. Since the flow in this apparatus is two-dimensional, two-dimensional interfacial roll waves can be produced to examine the entrainment rate—roll wave relationship.

SECTION I

INTRODUCTION

This is the twelfth quarterly report on the work done under Contract AT(04-3)-189, Project Agreement No. 44, and covers the period from July 1 to September 30, 1968.

The objectives for Phase 1 of the program were as follows:

Task A

1. Obtain detailed measurements of flow structure (pressure drop, liquid film thickness, wall shear stress, local mass flux, local impact pressure) for air-water and steam-water mixtures. Three series of tests are to be performed:
 - a. Air-water mixtures in a vertical annulus,
 - b. Air-water mixtures in a vertical nine-rod assembly, and
 - c. Steam-water mixtures at high pressure (600 to 1400 psia) in a vertical nine-rod assembly.
2. Carry on an analytical effort in parallel with the air-water tests.

Task B

1. Measure the critical heat flux for a vertical nine-rod geometry, under forced convection conditions, with water at high pressure (600 to 1400 psia) and flow upward. Tests to be performed with a "clean" multirod geometry (as little disturbance as possible to the flow by the provisions for maintaining the rods in correct relative alignment).
2. Investigate the effect of certain parameters; specifically, quality, flow rate, heated length, pressure, and rod-wall spacing.
3. Use the results to evaluate one or more computer models as a basis for CHF prediction.

With respect to Task B, Item 1, it had originally been intended to also run tests with grid-type spacers typical of current reactor practice. The feasibility of such tests depended on the successful development of heater rods with grounded sheaths. The rods were not developed in time, so this part of Task B has been transferred to Task D.

With respect to Task B, Item 3, it had been the intention to develop a model, drawing on the knowledge generated in Task A, which could be used to predict CHF in a multirod array. The Task B results could then be compared with the model predictions. It became apparent, however, that such a model would not be an improvement over certain computer models under development elsewhere; e. g., the COBRA code at Battelle Northwest Laboratory. The scope of Task B was then changed to include evaluation of one or more of these other models.

The work under Phase 1 has been reported in Quarterly Report Numbers 1 through 10, plus certain topical reports and "Final Summary" reports, either issued or to be issued soon.

The objectives for Phase 2 are as follows.

Task C

1. Make measurements of both fully-developed and developing two-phase flow (steam-water at 600 to 1400 psia, adiabatic and with heat addition, flow vertical upward) from which can be determined rates of mass and energy transfer in the transverse direction, such measurements to be made in a circular tube, eccentric annulus, and nine-rod channel.
2. Determine the relationships between rate and driving potential, or potential gradient, and the effect of certain parameters (e. g. , total flow, pressure, local void) on these relationships. In particular, determine the effect of grid-type spacers in the nine-rod channel.
3. Analyze the results to evaluate existing models of two-phase flow. Endeavor to develop an improved model in light of the results. Such a model should be useful in the prediction of flow structure, pressure drop, and critical heat flux in developing two-phase flow in multirod geometries, both "clean" and with grid-type spacers.

Task D

1. Measure critical heat flux in a nine-rod channel fitted with grid-type spacers characteristic of modern water-cooled reactors.
2. Determine, if possible, whether, and to what degree, the effect of spacers on the CHF is due to a redistribution of the flow among the various subchannels, or to a highly localized disturbance which might, for example, disrupt the liquid film.
3. Modify the prediction methods developed in Task C as appropriate, and check them against the data obtained under Item 1.

Progress during the quarter ending September 30, 1968, is described in the following sections.

SECTION II

ENTRAINMENT FRACTION

IN ADIABATIC ANNULAR-DISPERSED TWO-PHASE FLOW

There is a need to predict liquid entrainment rates along a developing two-phase annular-dispersed flow. However, the phenomena of liquid entrainment and deposition are complicated. As a beginning, a description of the entrainment fraction in the gas core for a fully-developed adiabatic two-phase flow would be a stride forward. (By definition, an asymptotic or fully-developed adiabatic two-phase flow is one where $d\rho_g/dZ$ is negligible and the entrainment fraction and dP/dZ remain essentially constant.)

Several investigators have suggested that large roll wave motions on the gas core-liquid film interface produce entrainment. For very thin films, these waves cease to exist and no further entrainment occurs. For fully-developed adiabatic conditions, the rate of entraining liquid into the air core equals the rate of depositing drops on the interface. Hence, any characteristic length associated with the interface area must be irrelevant in determining the asymptotic entrainment fraction.

Using the idea that the characteristic length is nondetermining, Paleev and Fillipovich⁽¹⁾ proposed that

$$\frac{\rho_g}{\rho_l} \frac{\mu_l G_g}{\rho_g \sigma}^2 = \frac{\mu_l^2}{\rho_l \sigma L} \frac{G_g^2 L}{\rho_g \sigma} \quad (1)$$

be the form for an entrainment fraction independent variable. Paleev and Fillipovich claim that the two dimensionless groups on the right side of Equation (1) are natural choices since they successfully correlate data from the interaction between a gas and a liquid during nozzle spraying. (Although they do not reference any nozzle spraying work, the work of Hinze⁽²⁾ supports their statement.) Taking into account the entrained liquid in calculating the core density, they modify Equation (1) by substituting $\frac{\rho_g}{\rho_l} \frac{1 + E G_l}{G_g}$ for $\frac{\rho_g}{\rho_l}$ to obtain:

$$\left(\frac{\rho_g}{\rho_l} \right) \left(1 + E \frac{G_l}{G_g} \right) \left(\frac{G_g \mu_l}{\rho_g \sigma} \right)^2 = \pi_1 \quad (2)$$

Using data from several sources,⁽¹⁻⁵⁾ they obtained

$$1 - E = 0.985 - 0.44 \log_{10} [\pi_1 \times 10^4] \quad (3)$$

as a fit through the mean of the data. For a given π_1 , most of the data points used by them fell within ± 0.1 around this line, which is presented in Figure 1. The asymptotic (fully developed) entrainment datum of the Gill, et al.,⁽⁷⁾ developing flow is in excellent agreement with Equation (3), as shown in Figure 2.

FIGURE 1. DATA PRESENTED BY PALEEV AND FILLIPOVICH (1)

MINH AND HUYGHE⁽⁸⁾

- × WATER ϕ 12 mm diameter
- WATER ϕ 6 mm diameter
- ALCOHOL ϕ 12 mm diameter

CISE DATA⁽⁹⁾, 2.5-cm diameter

- ◻ ARGON - ALCOHOL
 - ◆ ARGON - WATER
- } FILM SAMPLING

SINGH DATA⁽¹⁰⁾

- 1/2-inch SINTER
- 1-inch SINTER
- ◊ 2-inch SINTER

GE FILM DATA (AIR - WATER)⁽¹¹⁾

- △ ROUND TUBE, 1-inch diameter
 - ◻ CONCENTRIC ANNULUS
 - ◊ ECCENTRIC ANNULUS
- } GF ROD AND TUBE,
1-inch-diameter TUBE,
0.5-inch-diameter ROD.

GIL, HEWITT, AND HITCHON⁽⁷⁾

○

FIGURE 2. FURTHER ENTRAINMENT DATA

The results of Minh and Huyghe⁽⁸⁾ for air-water and air-alcohol flows in round tubes are shown in Figure 2. These data alone examine the effects of cross-sectional area and different fluid properties on the entrainment fraction. These data were taken over a range of pressures from 1 to 8 atm. The liquid film was sucked off through a uniform width slit around the tube perimeter. All the film liquid was assumed to be removed when an increase in slit width produced no increase in the flow rate of removed liquid. The entrainment fraction between $L/D = 80$ and $L/D = 300$ was reported unchanged, indicating a fully-developed condition. Apparently, independent of Paleev and Fillipovich, they deduced a kinetic energy per unit volume parameter,*

$$\frac{G_g}{\rho_g} \left(1 + E \frac{G_\ell}{G_g} \right)^2, \quad (4)$$

that correlates the area and density effects in their air-water data. As shown in Figure 2, their air-water and air-alcohol data are nearly superimposed when plotted in terms of π_1 .

Alia, et al.,⁽⁹⁾ report film liquid flow rate data at $L/D = 140$ for argon-alcohol and argon-water flows. An isokinetic sampling scoop, forming a segment of an annulus, was traversed through the liquid film to obtain the total liquid flowing between the wall and some position y in the film. The thickness of the liquid film was determined by a film conductance method. These results, shown in Figure 2 in terms of π_1 , are in basic agreement with the results of Minh and Huyghe, although the air-water results appear low. (Alia, et al., also present E versus flow quality curves [Figure 32 of Reference 9] smoothed through their air-water data. Evaluating these curves in terms of π_1 , the results surround the Minh-Huyghe data.)

The 1000-psia adiabatic steam-water round tube entrainment results of Singh, et al.,⁽¹⁰⁾ are shown in Figure 2 in terms of π_1 . These data, obtained by suction through a porous sinter at $L/D = 200$ from the entrance, fall below the correlation of Paleev and Fillipovich. Longer sinter lengths were used for higher total mass flow rates in an effort to catch all liquid in the film.

The air-water entrainment data of the present investigation⁽¹¹⁾ are presented in Figure 2 in terms of π_1 for the round tube and the concentric and eccentric annulus. These data were taken under constant air flow rate—variable water flow rate conditions at essentially the same pressure and temperature by sucking off the film through 1-inch-long porous sinters 12 feet from the entrance. The flow is presumed to be fully developed, since isokinetic sampling profile measurements at 9 and 10.5 feet from the entrance were identical (within the uncertainty of the isokinetic sampling technique).

There appear to be three general groupings from these data:

- a. The data that are fairly well correlated by Equation (3). These data were taken by core liquid flow rate sampling techniques, with the exception of the Dowtherm and carbon dioxide data of Mondin and Huyghe who employed the peripheral slit technique used by Minh and Huyghe.

* Minh and Huyghe suggest that Equation (4) be divided by $\bar{\alpha}^2$; for high flow qualities, $\bar{\alpha} \rightarrow 1$, and Equation (4) becomes more nearly correct.

- b. The slit and scoop data of Minh and Huyghe and Alia, et al., that fall above Equation (3).
- c. The porous sinter data of Singh, et al., and the present investigation, that fall below Equation (3).

At first glance, it would appear that E is either not a unique function of π_1 or improper properties are contained in π_1 . However, each set of these data taken on a given apparatus with a given measurement technique is self-consistent with the E versus π_1 formulation. The data of Minh and Huyghe show the effect of changing all variables in π_1 , although μ_ℓ and ρ_ℓ for water and alcohol are nearly the same. The data of Alia, et al., show mainly the effect of the surface tension for argon-water and argon-alcohol flows. With the exception of the Mondin and Huyghe work, the remaining investigations used water as the working liquid.

The data of Steen⁽¹²⁾ are plotted in Figure 3. These data, taken at $L/D \approx 90$ for air-silicone, air-ethylene glycol, and air-water flows, examine the effect of different fluid properties with substantial variations in μ_ℓ . The air-water data agree with the data of Minh and Huyghe, but the remaining data fail to correlate with π_1 .

Only in Steen's experiments was μ_ℓ varied substantially such that the liquid viscosity dependence could be examined. Because these data indicate that a higher liquid viscosity results in higher π_1 , but lower E , an empirical viscosity ratio factor to correct π_1 was derived from the silicone data. (The silicones have essentially the same ρ_ℓ and σ but μ_ℓ varies from 5 to 100 cP.) This viscosity factor is

$$\left(\frac{\mu_g}{\mu_\ell} \right)^{11/5}$$

normalizing on the gas viscosity, which varies little in all these data. Hence

$$\pi_3 = \pi_1 \left(\frac{\mu_g}{\mu_\ell} \right)^{11/5} = \frac{\rho_g}{\rho_\ell} \left(1 + E \frac{G_\ell}{G_g} \right) \left(\frac{G_g \mu_g}{\rho_g \sigma} \right)^2 \left(\frac{\mu_g}{\mu_\ell} \right)^{1/5}$$

should correlate the effect of liquid viscosity as well as the effect of properties correlated by π_1 . The parameter π_3 is in substantial agreement with Steen's parameter π_2 since

$$\pi_3 = \pi_2^2 \left(1 + E \frac{G_\ell}{G_g} \right) \left(\frac{\mu_g}{\mu_\ell} \right)^{1/5},$$

where

$$\pi_2 = \frac{G_g \mu_g}{\rho_g \sigma} \left(\frac{\rho_g}{\rho_\ell} \right)^{1/2}$$

and the liquid viscosity plays a lesser role than the gas viscosity.

As shown in Figure 4, Steen's air-water and air-ethylene glycol data are nearly superimposed on the air-silicone data when plotted in terms of π_3 . These data correlate with the

FIGURE 3. DATA OF STEEN⁽¹²⁾

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FIGURE 4. STEEN'S ENTRAINMENT DATA IN TERMS OF π_3

Minh and Huyghe, and Alia, et al., data which, in turn, are better correlated by π_3 than π_1 , as shown in Figure 5. The equations

$$1 - E = 0.819 - 0.112 \ln \left| \pi_3 \times 10^7 \right| \quad (5a)$$

for $\pi_3 < 4.5 \times 10^{-7}$ and

$$1 - E = 0.966 - 0.210 \ln \left| \pi_3 \times 10^7 \right| \quad (5b)$$

for $\pi_3 > 4.5 \times 10^{-7}$ fit these data, as shown in Figures 4 and 5.

The data of Singh, et al., and the present investigation do not correlate with the other data in terms of π_3 . Likewise, the ambient temperature air-water data that correlate with Equation (3) are merely shifted by nearly the same viscosity ratio factor and will not correlate with the Steen, Minh and Huyghe, and Alia, et al., data.

In conclusion, there is considerable evidence that the E versus π_3 formulation contains proper parameters for fully-developed, adiabatic, two-phase, annular-dispersed flows. Although all the results from these several investigations do not agree, the results from a given apparatus with a given measurement technique are self-consistent with the E versus π_3 formulation when parameters contained in π_3 are varied.

It is difficult to assess which of the measurement techniques is best since no investigation has been concerned with obtaining entrainment data by more than one method. Steen⁽¹²⁾ has shown that the one radial position core liquid sampling technique he used is weak at obtaining high entrainment data, the results being probe position and size dependent. However, because Steen used the same size probe at the same radial location for the air-silicone data used here, it is felt that the qualitative property dependence shown by his data is valid. The spacer results of Alia, et al.,⁽¹³⁾ indicate that small protrusions from the walls can produce further entrainment. This could be the case for the data of the present investigation, since slight misalignment of the void fraction quick closing valves upstream of the porous sinters could have produced a low film flow rate, as the data indicate. As pointed out in Reference 11, there is some uncertainty in interpreting the flow rate results from the porous sinter method. The isokinetic scoop and peripheral slit techniques data are consistent and probably disturb the flow the least. Hence, it is concluded that some of the data discussed here are rig-and-measurement-technique dependent. In light of this discussion, it is also concluded that the data of Minh and Huyghe and Alia, et al., are likely to be the best quantitatively.

More careful fully-developed flow entrainment experiments with careful measurement of all flow structure quantities (dP/dx , α , film thickness, wave structure, film liquid flow rate, and isokinetic sampling to obtain air-water velocity profiles) at several axial positions would indicate whether the flow was fully developed and would help resolve the proper E versus π_3 relationship, as well as provide more information about the entrainment phenomena.

FIGURE 5. ENTRAINMENT IN TERMS OF π_3

SECTION III

A COMMENT ON GAS LINEAR VELOCITY
PROFILES IN ROUND TUBES

In fully-developed, turbulent, single-phase flow in a round tube, a definite core ($y/R \gtrsim 0.05$) velocity profile similarity has been established; namely,

$$\frac{U_g - U}{U_\tau} = f(y/R) \quad (6)$$

where

$$f(y/R) \sim \ln |y/R|$$

as the wall is approached.⁽¹⁴⁾ One would expect that for a low entrained liquid annular two-phase flow, the formulation of Equation (6) may well hold for the gas linear velocity

$$U_g = G_g / \rho_g \propto \quad (7)$$

The gas linear velocity results of the present investigation are shown in Figure 6 to be substantially independent of mean flow quality within the scatter of the results. The experimental gas linear velocity results of Alia, et al.,⁽⁹⁾ are shown in Figure 7 for fully-developed annular dispersed flows. These sets of data are in close agreement for $y/R > 0.1$. (All these data were obtained by isokinetic sampling and impact pressures. Near the wall, the isokinetic probe interferes with the liquid film so that the isokinetic sampling results from both investigations for $y/R < 0.1$ are not completely reliable.) Apparently, the constant local slip ratio assumption of Alia, et al., in reducing their data produces nearly the same results as obtained in the present investigation using a variable local slip ratio assumption.⁽¹⁵⁾

Also shown in Figures 6 and 7 are the single-phase turbulent flow results of Laufer⁽¹⁶⁾ for the pipe, and Wieghardt⁽¹⁷⁾ for the flat plate. These single-phase results have been theoretically described by

$$f(y/R) = -\frac{1}{0.4} \ln |y/R| + g(y/R) \quad (8)$$

for large Reynolds numbers.⁽¹⁴⁾ Note that Equation (8) is composed of a logarithmic term and a large eddy correction term, the latter being slightly different for the pipe and the flat plate.⁽¹⁴⁾ The gas linear velocity results are seen to fall between the pipe and flat plate results. This is not surprising since the single-phase pipe flow is constrained by the walls, while the flat-plate flow can propagate into the freestream. The two-phase annular flow is constrained within the pipe, but the interface between the liquid film and the core remains free. Hence, the large eddy structure of the two-phase annular core flow is likely to be a combination of pipe and flat-plate characteristics, as indicated by the data.

Alia, et al., fitted

$$f(y/R) = \frac{1}{K} \ln |y/R| \quad (9)$$

FIGURE 6. DATA OF THE PRESENT INVESTIGATION

FIGURE 7. DATA OF ALIA, ET AL. (9)

to their data $y/R > 0.1$, obtaining $k = 0.03$. They contended that the liquid droplets decreased the turbulence level in the core since single-phase flows were known to produce $k = 0.4$. It should be noted that in single-phase flow, the region $y/R < 0.1$ is fitted with the logarithmic Equation (9), while the region $y/R > 0.1$ is also described by an additive large eddy turbulence function such as the one contained in Equation (8). Thus, this interpretation of the effect of droplets on turbulence level need not hold to explain the gas linear velocity profile. Equation (8), with a hybrid large eddy term from the pipe and flat plate single-phase flows, appears to be applicable to the gas linear velocity profiles for annular dispersed flows with qualities greater than 11%.

SECTION IV

LOW-PRESSURE CHANNEL

A low-pressure, horizontal channel has been constructed in Building P at APED to facilitate the evaluation of film thickness and flow rate measurement techniques. This air-water apparatus shown in Figures 8 and 9 has a 1 x 6 inch plexiglass flow channel 4 feet long, with a ground glass bottom. The ground glass is more easily wetted than plate glass or plexiglass, and was chosen so that low liquid flow rates could be examined. The bottom was carefully leveled such that at low water flow rates there was no preferential flow along either side.

Air, furnished by a blower, passes through a plenum, where it is mixed. This flow passes through a wire cloth, 4:1 area ratio nozzle, and is straightened by honeycomb before entering the test section. Air velocity profiles measured across the test section by a six-probe pitot rake (Figure 10) indicate the flow is two-dimensional within 2% in velocity over the center two-thirds of the test section.

Soft water is pumped from a reservoir through a filter, calibrated rotameters, and a plenum, before entering the test section. The water flow entrance is a uniform height (1/16 inch), 2-inch-long channel formed between the test section bottom and a lip from the top of the water plenum.

To date, the flush electrode conductance cell film thickness technique described in the Eleventh Quarterly Progress Report⁽¹⁸⁾ and the porous sinter film liquid flow rate technique⁽¹⁹⁾ have been examined. A 1/8-inch-diameter electrode, 3/4-inch spacing cell with the corresponding calibration curve, as described in Reference 18, was installed 3 feet from the water entrance. Two lengths of sintered bronze were installed, with the 1-inch-long sinter located 3 inches upstream of the conductance cell and the 2-inch-long sinter 3 inches downstream of the cell. Care was taken to eliminate discontinuities between the porous sinters and the glass bottom.

Six quantitative data runs were made for flows without liquid entrainment in the air flow. Static pressure drop, air velocity profiles, liquid flow rate, and film thickness measurements were made. The bottom wall shear was deduced from the relation

$$\tau_w = -h \, dP/dz$$

since it was determined experimentally that $\partial U/\partial z = 0$. Using these results, the air velocity profiles normalized on U_τ were plotted in the velocity-defect form as shown in Figure 11. These profiles, like those of Figures 6 and 7, fall between the single-phase pipe results of Laufer and the flat-plate results of Wieghardt, and strengthen the conclusions discussed in Section III.

The film thickness-flow rate data are shown in Figure 12 in terms of

$$G_f^+ = \frac{G_f \delta}{\mu_\ell} \quad \text{and} \quad \delta^+ = \frac{\delta \rho_\ell}{\mu_\ell} \sqrt{\frac{\tau_w}{\rho_\ell}}$$

FIGURE 8. LOW-PRESSURE AIR — WATER CHANNEL

FIGURE 9 LOW-PRESSURE AIR — WATER CHANNEL

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FIGURE 10. SIX-PROBE PITOT RAKE IN TEST SECTION

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FIGURE 11. AIR VELOCITY PROFILES, LOW-PRESSURE CHANNEL

FIGURE 12. FILM FLOW RATE — THICKNESS DATA

Note that these data fall closer to the Von Kármán theory as applied by Levy⁽²⁰⁾ than the model developed in the Eleventh Quarterly Report.⁽¹⁸⁾ This is not surprising since no void in the film and no roll waves on the interface were observed for these data. This result indicates the applicability of the zero void mixing length model to films without void. If this is so, it is necessary to account for voids in order to describe the data from flows with entrainment and roll waves, as done in the analysis of Reference 18. These data indicate that the flush electrode conductance cell of Reference 18 can be successfully used to determine the mean film thickness of thin films.

On several preliminary qualitative runs with liquid entrainment, two-dimensional large roll waves were observed on the liquid surface. The fundamental frequency of these waves was determined by using the two conductance electrodes whose axis is normal to the flow direction. The amplitude of these waves was of the order one-half the mean thickness, while the wave frequency was 10 to 15 Hz. It is suggested that future investigations of film flow characteristics consider using the flush electrode cell to obtain interfacial wave frequency data.

A vacuum pump (Figures 8 and 9) was used to suck off film liquid through the porous sinters into a measuring tank. Due to the lack of suction capacity, only the lowest flow rate case has been examined to date. The measured flow rate through the 2-in. porous sinter was determined to be 81% of the rotameter determined flow rate, the large error being caused by the measurement of a small quantity of liquid over a long period.

Due to nonuniform porosity ($\pm 5\%$) of the sinters, the liquid was not sucked off uniformly. As a result, at certain mean flow rates liquid was completely removed at some lateral locations on the sinter, while at other lateral locations part of the liquid escaped. This problem could conceivably lead to the underestimation of film liquid flow rate since some liquid could escape at one lateral location while gas is drawn off at another. Hence, the sucked liquid-gas flow rate curves (Figure A-16 of Reference 21) could still be formed with film liquid escaping.

In conclusion, a low-pressure, horizontal, air-water flow channel has been constructed to produce two-dimensional air and water flows. Film liquid flow rate data and film thickness data have been obtained, indicating that the flush electrode cell technique can be used to measure the thickness of thin films. Since two-dimensional roll waves can be produced in this apparatus, this apparatus is qualified for performing interface wave experiments to examine the entrainment rate—roll wave relationship.

NOMENCLATURE

D	Tube diameter [L]
E	Entrainment fraction
G	Mass flux [M/L ² T]
h	Distance from wetted wall to point of maximum air velocity [L]
L	Characteristic length; also axial length
P	Pressure [F/L ²]
R	Tube radius [L]
U	Local velocity in flow direction [L/T]
U_{τ}	$\equiv \sqrt{\tau_w/\rho_g}$, [L/T]
y	Distance measured from wall [L]
Z	Axial length [L]
α	Local void fraction
$\bar{\alpha}$	Average void fraction
δ	Mean liquid film thickness [L]
μ	Dynamic viscosity [F - T/L ²]
ρ	Density [M/L ³]
σ	Surface tension [F/L]
τ	Shear stress [F/L ²]

Subscripts

$\mathcal{C}_L$	Tube centerline value
f	Film
g	Gas phase
l	Liquid phase
max	Maximum value
w	Wall value

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