Liquid Film Flow-Rates in Two-Phase Flow of Steam and Water at 1000 Lb./Sq. In. Abs.

KULDIP SINGH and C. C. ST. PIERRE
University of Windsor, Windsor, Ontario

W. A. CRAGO and E. O. MOECK
Atomic Energy of Canada Limited, Chalk River, Ontario

A knowledge of liquid-film flow rates is important for design purposes when accurate predictions are required of the conditions under which dryout heat flux occurs in nuclear reactors and boilers. Liquid-film flow rates were measured for a steam-water mixture in cocurrent, upward annular flow in a tube at a pressure of 1,000 lb./sq.in.abs. Sinters located at the test section exit were used to extract the liquid film after the method of the Harwell group. Sinter lengths of 2, 1, and ½ in. were employed to investigate the effect of length on the extracted liquid flow rates. The test section was a stainless steel pipe of inside diameter 0.493 in., approximately 200 diam. in length. The total mass flux ranged from 0.2 to 0.7 $\times$ 10^6 lb.m/hr.sq.ft. and the quality varied from 0.3 to 0.92.

The experimental film flow rates were found to increase with decreasing quality. In the range of parameters investigated, the curves of film flow rate at constant quality vs. mass flux showed a maximum at a fixed value of steam velocity. At the same total mass flux and quality the film flow from the ½ in. sinter was lowest, suggesting that the crests of high amplitude roll waves overshot the sinter. Film flow rates were consistently higher than the theoretical predictions using Levy's model. About one-third of the measured flow rates were twice as high as predicted.

For a number of years now the phenomenon of critical heat flux or burnout associated with two-phase flowing systems has received considerable attention from innumerable investigators. One of the important parameters related to the critical heat flux is the liquid film flow rate at the wall (*1*). This is especially true for high quality annular flow in which dryout of the film near the wall leads to the flow boiling crisis.

The object of the present work was to measure the liquid film flow rate at elevated pressures by use of a sinter located at the exit end of a test section. The effect of sinter length, pressure, total mass flux, and quality on the film flow rate was studied. The test section employed was a ⅜ in., Sch 40, stainless steel pipe (I.D. 0.493 in.). The length of the test section was about 200 diam.

Sinter lengths of 2, 1 and ½ in. were used. The total mass flux was varied from 0.2 to 0.7 $\times$ 10^6 lb.m/hr.sq.ft. and steam quality ranged from 0.3 to 0.92. Runs were made at pressures of 1,000 and 1,200 lb./sq.in.abs. However, only limited data were obtained at a pressure of 1,200 lb./sq.in.abs. so that no generalized effects of pressure on film flow rates can be given.

The experimental liquid-film flow rates were compared with the theoretical model proposed recently by Levy (*2*).

SURVEY

Liquid Film Flow Rate Measurement

An extensive review of various techniques for measurement of liquid-film flow rates has been given by Collier and Hewitt (*1*) in a recent paper. The first attempt to measure the liquid film flow rate by employing a porous sinter was made by Gill and Hewitt (*3*). Since then a number of workers (*4* to *7*) have successfully measured the film flow by employing a sinter in the following manner. The sinter whose internal diameter is the same as that of the test section, is located at the exit of the test section. Care is taken to ensure that the bore is continuous and that there are no ridges at the various joints. Suction is then applied on the outside of the sinter to remove the liquid flowing along the tube wall.

In all experiments of this type, each investigator used a different sinter length. Hewitt (*4, 6*) chose a sinter length of 0.5 in., Staniforth (*5*) employed a 2.5 in. sinter and Cousins (*7*) used a 3 in. length. It was not known if the sinter length had any effect on the measurement of liquid-film flow rates. However, too long a sinter could capture additional water from the core whereas crests of high amplitude roll waves would probably miss a shorter sinter.

Models for Predicting Liquid Film Flow Rates

Many theoretical models for two-phase annular flow have been proposed (*8* to *11*). Reviews of papers up to 1958 have been made by Charvonia (*12*) and Bennett (*13*). All these analytical studies considered only the simplified case of a liquid film and gas core with a smooth interface and no liquid entrainment.

In a recent paper, Levy (*2*) has presented a semi-empirical model for the prediction of liquid film flow rates in annular flow with entrainment. He considered the momentum and mass transfer component of the interfacial shear. Levy showed that the momentum term is dominant within the liquid film while the mass transfer term is the important component within the gas core.

Assuming that the liquid film thickness is small and that the gas density is much smaller than the liquid density, Levy arrived at the following simplified equation:

$$\sqrt{\frac{(-dp/dL)(D/4)g_c}{\rho_l}}\,\frac{\rho_g}{G_g}\,R\left(\frac{\rho_l}{\rho_g}\right)\left(\frac{\rho_l}{-dp/dL}\,\frac{g}{g_c}\right)^{-n} = F\left(\frac{2t}{D}\right) \quad (1)$$

In the above equation, the function $R(\rho_l/\rho_g)$ was introduced from semi-empirical considerations to account for slip of the gas with respect to the liquid particles contained in the core. Universal application of the function $F(2t/D)$ was established by using data taken by the Centro Informazion Studi Esperienze (*14*) team at various liquid and gas phase densities and over a wide range of liquid and gas flow rates.

By analogy with single phase flow, velocity profiles in the liquid film were evaluated. Film flow rates were obtained by integrating these velocity profiles. The treatment was limited to situations where y^+, the Reynolds number based on the friction velocity, was greater than 30.

The correlation obtained was tested with film flow rate data for air-water mixtures obtained by Gill and Hewitt (*3*) at atmospheric pressure. As pointed out by Levy, the proposed model gave an approximate, yet acceptable, prediction of film flows for two-phase annular flow. One set of calculations was performed for upwards flow of steam-water mixture at a pressure of 1,000 lb./sq.in.abs. in a smooth ½ in. diameter pipe. However, no experimental data were available then to confirm these calculations. Need for taking additional experimental data was pointed out by Levy to further check and improve the analytical model.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Equipment

The experimental equipment consisted essentially of a test section, two high pressure boilers, a preheater, a superheater, a condenser, two high pressure pumps, two coolers, a mixer, and a number of flow measuring devices.

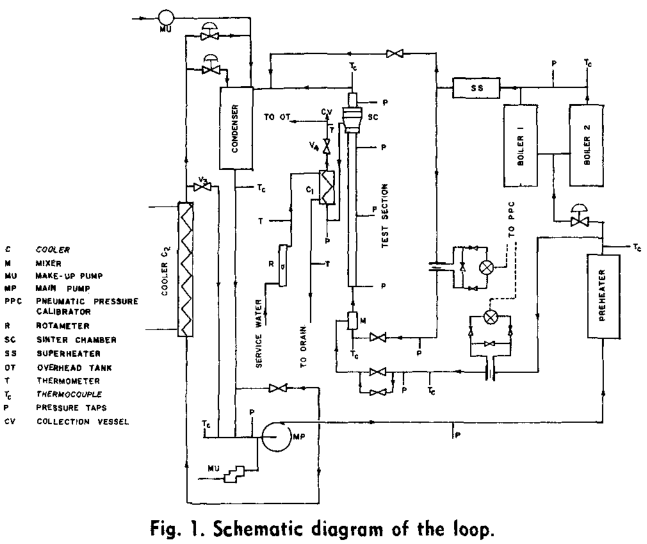

Fig. 1. Schematic diagram of the loop.

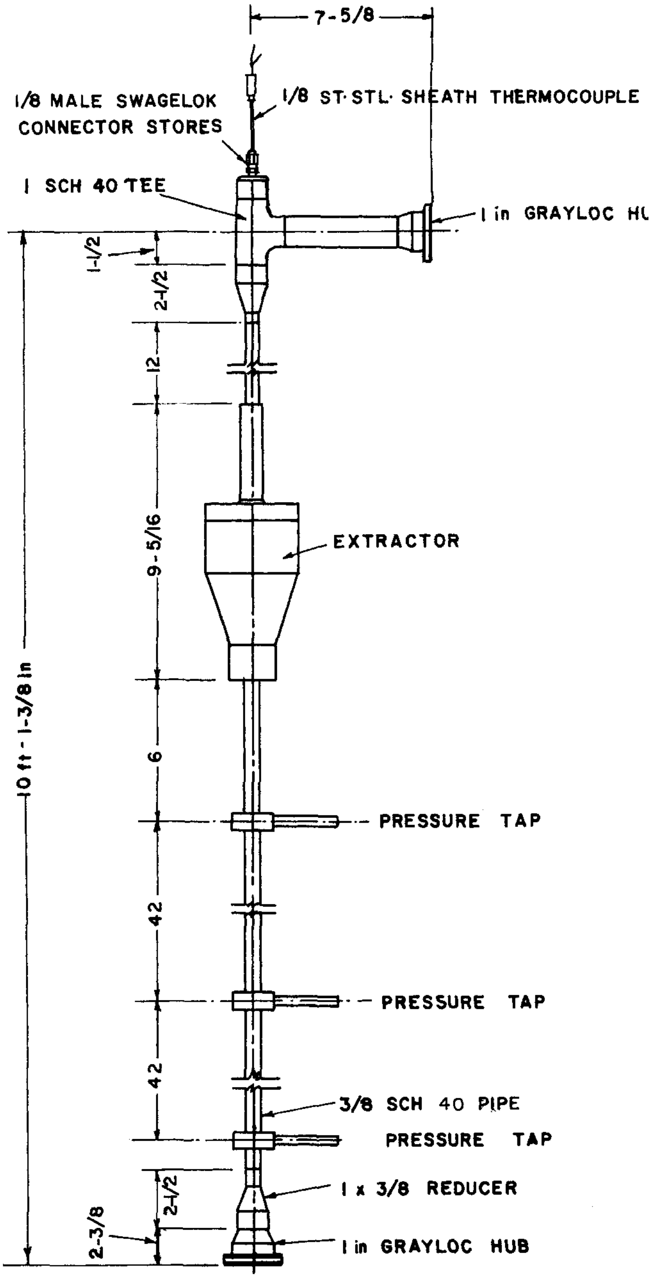

Fig. 2. Test section details, (all dimensions in inches).

A schematic diagram of the high pressure experimental loop is given in Figure 1. Steam from the electrically heated boilers passed through a superheater, an orifice plate connected to a differential pressure (D. P.) cell and then via a throttle valve to the mixer. The superheater was electrically heated and consisted of three hairpin elements having a power rating of approximately 7 k.w. each. A Bingham high pressure centrifugal pump of capacity 36 Imperial gal./min. at 300 ft. head supplied water to the preheater. An orifice plate and a throttling valve measured and metered the flow to the mixer. In the preheater were three heating coils with a power rating of 12 k.w. each and one heating coil with a power rating of 72 k.w.

A multijet injection type mixer was constructed from a 1 in. Sch. 40 tee fitted with a 0.493 in. I.D. pipe between the straight through ends. Steam flowed upwards through this tube and water was added from the surrounding annular space through six ⅛ in. diameter holes in the tube wall.

Steam-water mixture from the mixer passed up the vertical test section. The high pressure test section was made from a ⅜ in. stainless steel (type 304), Sch. 40 pipe with an inside diameter of 0.493 in. (thickness 0.091 in.). Test section details and the position of various pressure taps are detailed in Figure 2. Three pressure taps were provided along the length

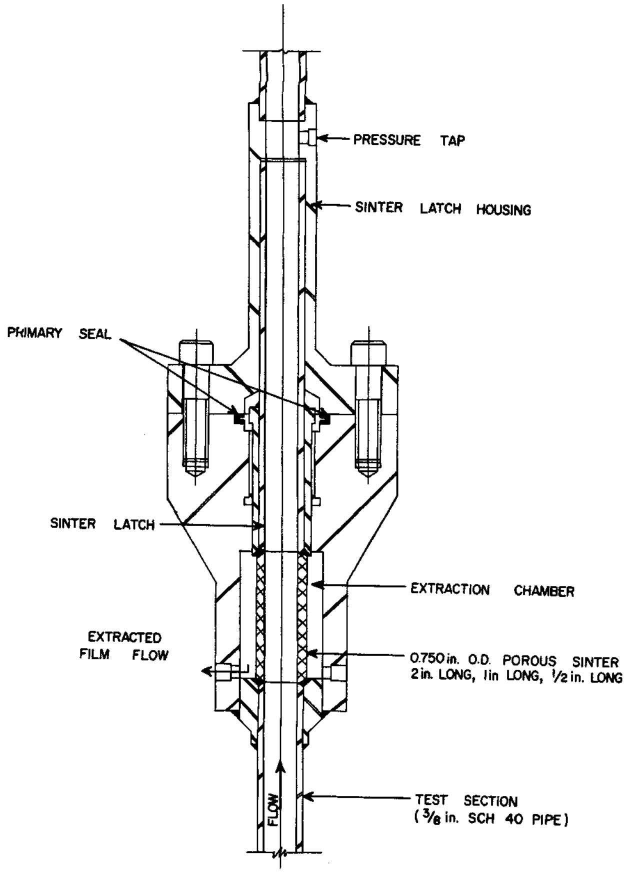

Fig. 3. Detail of liquid film extractor.

of the test section at intervals of 3.5 ft. with one pressure tap at a distance of 6 in. upstream from the sinter.

The stainless steel sinter was mounted approximately 7½ ft. from the inlet of the test section. This length of 200 diam. is believed to be sufficient to allow for fully developed void and velocity profiles to be established. The design of liquid film extraction chamber is shown in Figure 3. A two piece design assembly utilizing only one seal was used. A screw thread on the outside of the sinter latch served as an adjustable clamp down device for the sinter and a partial seal against back leakage. The extracted liquid, together with small amounts of steam from the main core, passed through a cooler C1 (Figure 1) which consisted of a 3/16 in. O.D. coiled pipe in an annular bath of cooling water.

The steam-water mixture from the top of the test section passed to a water cooled condenser. From the condenser, the water flowed to the inlet of the main centrifugal pump. Makeup water for the liquid extracted through the sinter was provided by a high pressure Aldrich reciprocating pump. A second makeup pump of smaller capacity was also available which pumped water from the storage tank to the inlet of the main centrifugal pump. Pressure in the condenser was controlled automatically.

Orifice meters with D.P. cells were used to measure the inlet water and steam flow rates. The flow rates measured in this manner were estimated to be accurate to within ± 2%. Oscillations of the system and reliance on the D.P. cell coupled with the pneumatic calibrator might have increased the likely error to the order of ± 4 to 5%. Pressure differential measurements across the flow metering orifices and across the test section were made with Foxboro differential pressure cells calibrated in the appropriate range. Cooling water flow required to condense and cool the extracted flows from the test section was measured with a Brook's rotameter with a range of 1.6 to 28 gal./min.

Water and steam temperatures at the inlet to the mixer and the temperature at the exit of the test section were measured by means of Chromel-Alumel thermocouples. Fisher thermometers with a range of —1 to 51°C. were used to measure inlet and outlet temperatures of the cooling water and the outlet temperature of the condensate from the cooler.

Experimental Procedure

Before any data were taken, the loop was hydrostatically tested to check for any leaks in the system. Experimental runs were made by introducing two separate streams of steam and water through the mixer to the test section inlet. The flow rates of both streams were adjusted by throttling valves downstream of the orifice as close as possible to the required conditions at the test section inlet. Power to the steam superheater was adjusted so that the steam at the mixer inlet was superheated about 10°C. The water stream passed through a preheater which raised its temperature to a few degrees below saturation. The steam superheat and the water subcooling were determined by accurately measuring the pressure and obtaining the equivalent saturation temperature. To control the water temperature within 2 or 3°C., it was necessary to adjust the inlet temperature of water to the preheater. This was accomplished by changing the flow rate of water to cooler C2 by means of valve V3 (Figure 1).

When steady state conditions were achieved, control valve V4 (Figure 1) was opened to adjust the pressure differential across the sinter so as to get a small extraction rate. The coolant water flow to exchanger C1 was adjusted so that temperature difference between inlet and outlet was approximately 10°C. Thermocouple, thermometer, D.P. cell, rotameter and pressure readings were recorded. For each run the total mass flux, quality, sinter length, and pressure were kept constant but different extraction rates through the sinter were obtained by varying the pressure differential across it. One of the four independent variables (mass flux, quality, sinter length, and pressure) was then varied and the previous set of data taken for the new experimental conditions.

The range of experimental parameters is shown in Table 1.

TABLE 1. RANGE OF EXPERIMENTAL PARAMETERS

Parameter	Range
quality	0.3 — 0.92
total mass flux	0.2 — 0.7 × 10^6 lb.m/hr.sq.ft.
pressure	1,000, 1,200 lb./sq.in.abs.
sinter length	2, 1, ½ in.

In any attempt to remove all of the liquid film from the wall, small amounts of steam phase are inevitably removed from the core. The two-phase mixture thus extracted is passed through a cooler and is condensed. In order to estimate the amount of liquid extracted, use was made of the following equation obtained by carrying out thermal energy balance over the cooler:

$$W_w = \frac{W_e H_s - W_e(T_7 - 32)C_p - W_c(T_9 - T_8)C_p}{H_s - H_w}$$

All thermodynamic properties were based on the test section temperature and pressure at the sinter. This was done since a portion of the water film would flash into steam while passing

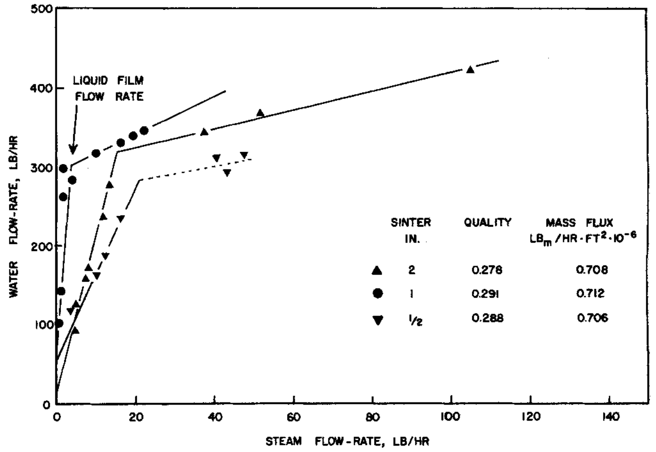

Fig. 4. Typical plot of steam flow rate vs. water flow rate through the sinter.

through the sinter.

A record was made of the total flow through and the pressure differential across the sinter. The flow rate was changed by varying the pressure differential across the sinter. By use of the above equation, liquid flow rates through the sinter were calculated. Steam flow rate through the sinter was then plotted against water flow rate as shown in Figure 4. On every plot, with a few exceptions, two distinct straight lines were obtained. At the intersection of these two lines, the steam flow rate began to increase rapidly. This point of intersection gave the liquid film flow rate.

RESULTS AND DISCUSSION

The effect of total mass flux, steam quality, pressure, and sinter length on film flow rates are reported here. The major portion of the data was taken at a pressure of 1,000 lb./sq.in.abs. with a few runs at 1,200 lb./sq.in.abs. The number of runs taken with different sinter lengths is shown in Table 2. A complete compilation of all the results is given elsewhere (*15*).

TABLE 2. SUMMARY OF EXPERIMENTAL DATA

Sinter Length, in.	Pressure lb./sq.in.abs.	Number of Runs
2	1,000	18
	1,200	4
1	1,000	13
½	1,000	11
	1,200	3

Liquid Film Flow Rates

The variation of experimental liquid film flow rates

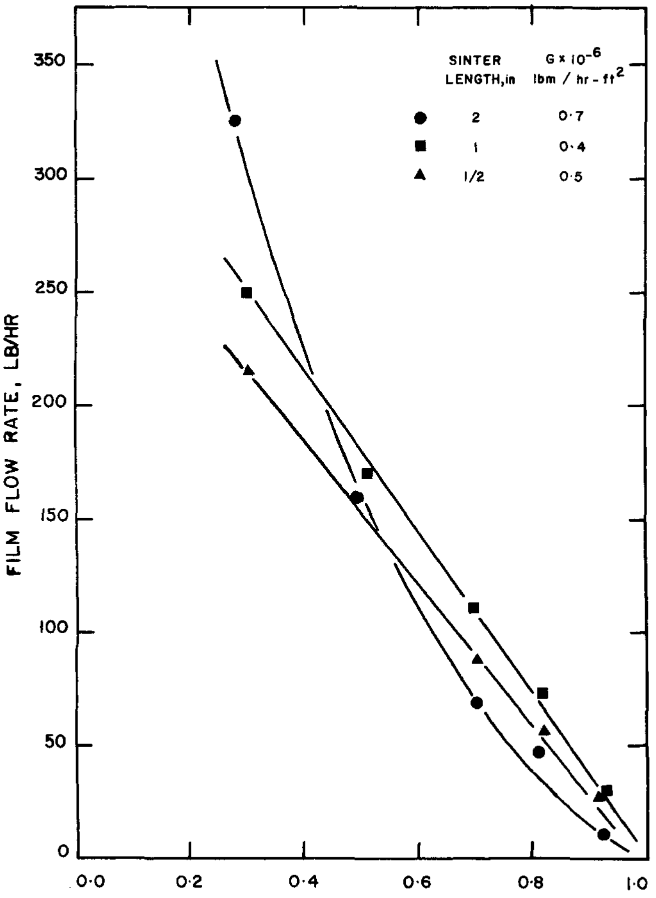

Fig. 5. Variation of film flow rates with quality.

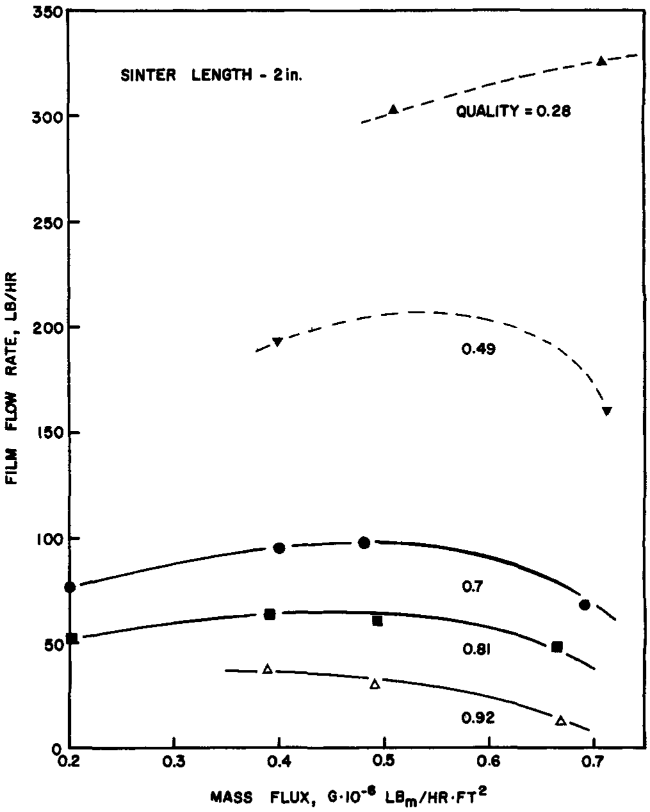

Fig. 6. Variation of film flow rates with mass flux at constant quality.

with quality at constant total mass flux and pressure has been shown in Figure 5 for three different sinter lengths. The liquid film flow rate decreased with increased steam quality at constant mass flux. Liquid film flow rates have been plotted as a function of total mass flux at constant quality in Figure 6. The film flow rates passed through a maximum value as the total mass flux was increased from 0.2 to 0.7 $\times$ 10^6 lb.m/hr.sq.ft. Employing Wallis' (*18*) criterion, it was verified that this maximum is not due to a transition from the semiannular to the annular flow regime; it occurs at a superficial steam velocity an order of magnitude higher than that for transition. The maximum film flow rate appears to occur at a constant value of the steam flow rate, that is, GX. For this reason the ratio of liquid film flow rate to the maximum film flow at a given quality has been plotted against kinetic energy of the gas stream in Figure 7. The data are now grouped in a single band. It appears that at a gas kinetic energy of about 50 ft.lb.f/cu.ft. the film flow rate is a maximum at a given quality. If the gas flow rate is increased, the quality being held constant by addition of liquid, the added liquid plus a small part of the film is entrained. Our results confirm the air-water data of Collier and Hewitt (*19*) and Gill and Hewitt (*3*). They too observed a maximum film flow rate at constant air mass fraction (quality) as the air velocity increased, as shown in Figure 8. The air kinetic energy at this maximum is about 40 ft.lb.f/cu.ft. which agrees well with our steam-water value. Unfortunately, Collier and Hewitt did not relate this maximum to their visual observations of the flow. It is our opinion that a flow redistribution takes place, that is, this maximum corresponds to the onset of roll waves at which point the entrainment starts increasing at a rapid rate.

Effects of Sinter Length

One of the major objectives of the present study was

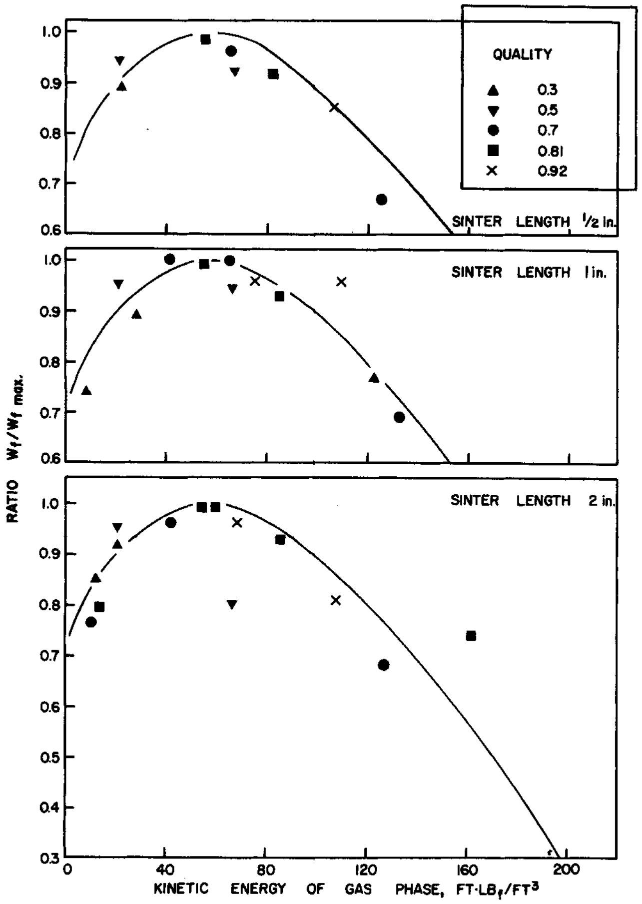

Fig. 7. Reduced film flow rate at constant quality as a function of gas kinetic energy for 1,000 lb./sq. in. abs. steam-water mixtures.

to investigate the effect of sinter length on the liquid film extraction rates under similar conditions of total mass flux and quality. For the same flow conditions, that is, constant steam quality and total mass flux, experimental liquid-film flow rates have been plotted against sinter length. Figure 9 is an example of such a plot. Generally the film flow rate increased slightly with increasing sinter length. This is to be expected for two reasons, extraction of liquid droplets from the core and total capture of large roll waves. Thus it appears that the ½ in. sinter extracted few droplets from the core and missed some of the roll

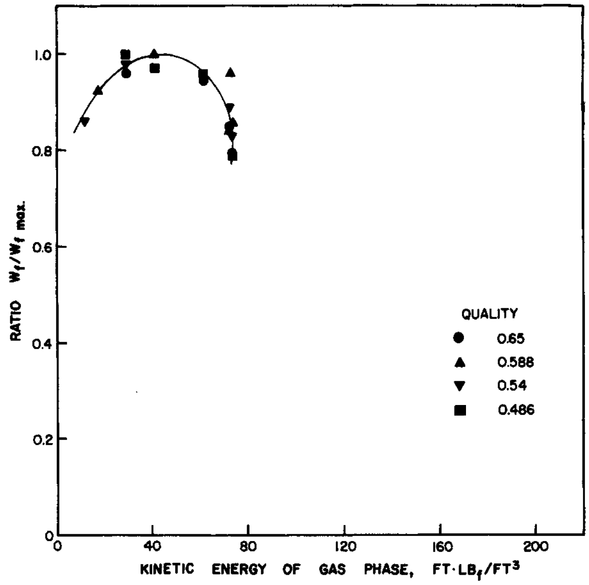

Fig. 8. Reduced film flow rate at constant quality as a function of gas kinetic energy for 14.7 lb./sq. in. abs. air-water mixtures.

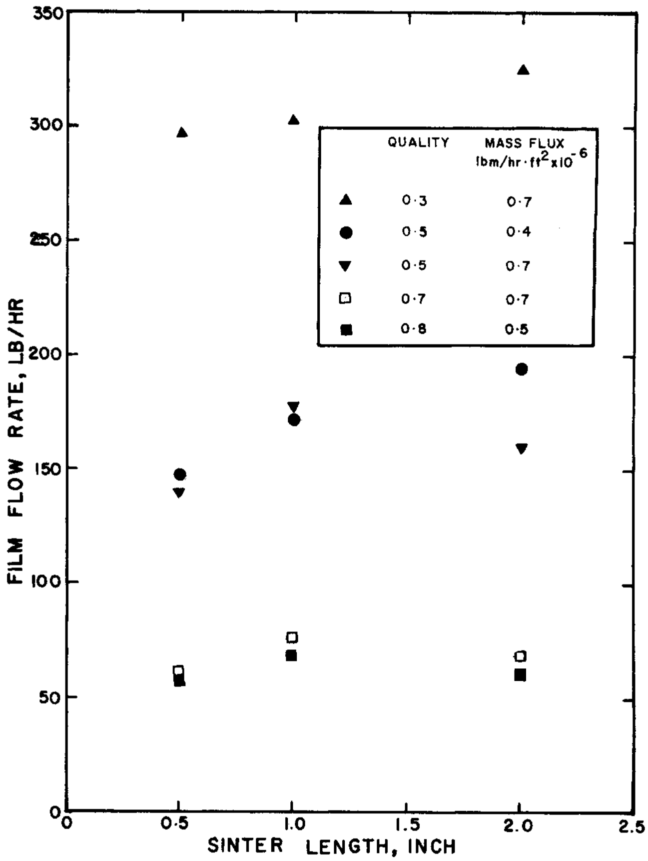

Fig. 9. Variation of film flow rates with sinter length.

wave crests.

An estimate of droplet capture can be made on the basis of the Harwell (*17*) deposition studies. We extrapolated their data to a mass flux of 0.7 × 10^6 lb.m/hr.sq.ft. and found that deposition amounts to no more than 2% (at quality of 0.3) to 3.5% (at quality of 0.7) of the extracted film flow for our 1 in. sinter. For the 2 in. sinter, this would be 4 to 7%. Because the extracted vapor would tend to drag droplets with it, the droplet capture could be marginally higher. A comparison of all the curves of liquid flow rate vs. vapor flow rate (such as Figure 4) showed that the 1 in. sinter always had the lowest vapor flow rate at the change of slope point. This suggests that the film flow rates obtained by the 1 in. sinter are closer to the true film flow than those measured by the ½ or 2 in. sinters.

An additional factor which reduced the reliability of the measured flow rates from the 2 in. sinter was inferred from Figure 9. In some runs, the 2 in. sinter extracted less liquid than the 1 in. sinter under nominally the same flow conditions. A check on the experimental data revealed that these runs were taken after the sinter had been in the loop for over four weeks.

During the experimental runs, it was noticed that the sinters became quite dark in color after use, indicating oxidation. Partial plugging of the 2 in. sinter due to oxidation is suspected since it remained in the loop for approximately 35 days while the shorter sinters were there for less than seven days. It is difficult to ascertain quantitatively the effect of this partial clogging on the extractive properties of the sinter with any degree of confidence. Most probably it will extract lower film flow.

Comparison with Levy's Model

Experimental liquid film flow rates were compared with the theoretical predictions by Levy's (*2*) analytical model. The value of y^+, the dimensionless Reynolds number based on the friction velocity, was more than 30 for all

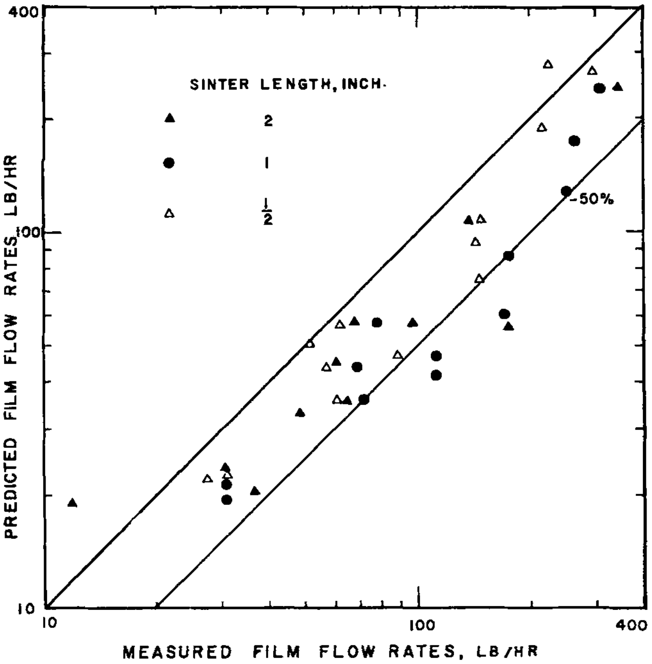

Fig. 10. Comparison of Levy's model with experimental data.

runs, thus indicating that Levy's analysis is applicable.

The measured values and the theoretical predictions for film flow rates are compared in Figure 10 for all the three sinter lengths. It is observed that the film flow rates as predicted by Levy's analysis were consistently lower than the experimentally observed values. About one-third of the measured flow rates were twice as high as predicted. Agreement is best for the ½ in. sinter flow rates because these were the lowest. However, as pointed out by Collier and Hewitt (*1*), a short sinter will extract less than the true film flow rate because the crests of high amplitude roll waves overshoot the sinter. We believe this to be the case for our ½ in. sinter and suggest that the 1 in. sinter data are the most reliable.

CONCLUSIONS

Experimental measurements have been made of the liquid-film flow rates for steam-water mixtures flowing in a vertical test section at high pressures. In order to extract the liquid film on the wall, sinters of various lengths were employed; a technique used previously by the Harwell group (*4* to *6*). An effect of sinter length on the extracted liquid film flow rates has been demonstrated.

At constant total mass flux, the liquid-film flow rate decreased as the quality was increased from 0.3 to 0.92, tending to zero at quality of 1. At constant quality, the liquid film flow rate passed through a maximum as mass flux was increased from 0.2 to 0.7 × 10^6 lb.m/hr.sq.ft. The experimental film flow rates have been compared with the theoretical predictions of Levy (*2*) for annular flow. It has been shown that the model predicts consistently lower film flow rates, with the deviation being as high as 64%. Agreement of theoretical predictions from the model with the experimental data obtained by use of a ½ in. sinter was much better than in the case of longer sinters. However, the flow rates obtained from this sinter were probably too low because crests of roll waves could overshoot the sinter. In our opinion the 1 in. sinter gave the most reliable film flow measurements.

ACKNOWLEDGMENT

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NOTATION

D = diameter, ft.
G = mass flux, lb.m/hr.sq.ft.
g_c = gravitational conversion factor, lb.m/lb.f ft./hr.
dp/dL = pressure drop per unit length, lb.f/cu.ft.
H_s = enthalpy of steam at the sinter, B.t.u./lb.m
H_w = enthalpy of water at the sinter, B.t.u./lb.m
n = exponent in Levy's equation, 0 if $(dp/dL) \geq g/g_c\ (\rho_l)$
1/3 if $(dp/dL) < g/g_c\ (\rho_l)$
t = thickness of the liquid film, ft.
T_7 = temperature of extract at outlet of cooler C1, °F.
T_8 = inlet temperature of coolant to Cl, °F.
T_9 = outlet temperature of coolant to C2, °F.
W_e = mass flow rate of extract through the sinter, lb.m/hr.
W_w = mass flow rate of liquid through the sinter, lb.m/hr.
W_c = coolant flow rate, lb.m/hr.

Greek Letters

ρ = density, lb.m/cu.ft.

Subscripts

g = gas or steam
l = liquid or water

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