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ADIABATIC STEAM–WATER ANNULAR FLOW IN AN ANNULAR GEOMETRY

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Abstract—Experimental results for fully developed steam–water annular flow in annular geometries are presented. Rod and tube film flow rates and axial pressure gradients were measured for mass fluxes between 500 and 2000 kg/m^{2}s, steam qualities between 20 and 60 per cent and pressures ranging from 3 to 9 MPa. It was found that the measured tube film flow rate per unit tube perimeter is always many times greater than the corresponding rod film flow rate. Possible explanations for this asymmetry are discussed.

INTRODUCTION

In fully developed annular two-phase flow, as it occurs in sufficiently long test sections, the film flow rate, gas velocity, droplet concentration in the gas core, etc. are independent of the axial coordinate. Only the pressure has a non-zero axial gradient. (The decreasing pressure does, strictly speaking, lead to changing fluid properties and, in particular, to an axially decreasing gas density. However, for the high pressure conditions considered here, this effect is without practical importance.)

The fully developed annular flow regime is of particular interest because of its relative simplicity. In the equilibrium situation the rate of entrainment from each film is exactly equal to the rate of deposition. Furthermore, since the walls are adiabatic, there is no evaporation from the films to complicate the situation.

For annular flow in an annular geometry two water films exist (a rod film and a tube film). The films interact via the gas core through liquid entrainment and deposition. The hydrodynamic situation is more complex than in the tubular case and is therefore a greater challenge to theoretical models.

High pressure steam–water equilibrium data for tube flow have been reported by several investigators: Singh *et al.* (1969), Keeys *et al.* (1970), Kirillov *et al.* (1973), Nigmatulin *et al.* (1976), and Würtz (1978). However, for annular geometries only one data set, Moeck (1970), has been reported.

EXPERIMENTAL RESULTS

The present experiments were performed under adiabatic conditions with steam–water at pressures ranging from 3 to 9 MPa. The vertical annular test section was 8 m long; the rod o.d. was 17 mm and the tube i.d. was 26 mm. The steam–water mixture was produced in an electrically heated steam generator and injected at the bottom of the test section. The rod and tube films were sucked off through perforations at the top of the rod and the tube. The perforations covered an axial length of 50 mm and consisted of numerous 1.2-mm holes. The rod was centered by means of four radial spacer pins every approx. 0.6 m of axial length. Each spacer pin was 2 mm in dia. and hemispherical at the point of contact with the rod. The last spacer level was 0.15 m below the perforations.

Static pressure taps were drilled in the tube wall at intervals of 0.5 m. The upper pressure tap was placed immediately below the perforation, the lowest 3.5 m below. The steam and water content of the mixture sucked off through the perforations were determined by condensing the steam in a heat exchanger and performing the necessary heat and mass balances.

The film flow rate, W_F, was determined by plotting the rate of liquid sucked off, W_L, vs the rate of steam sucked off, W_G, and then extrapolating to zero steam flow rate as illustrated in figure 1. The experimental data are tabulated in table 1.

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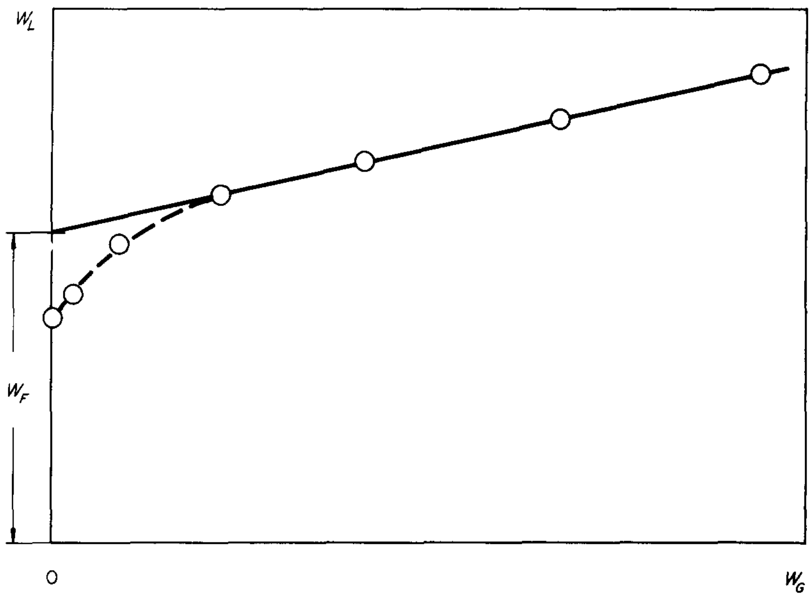

Figure 1. Method of determining the film flow rate W_F. W_L and W_G are the rates of liquid and steam, respectively, sucked off through the perforation.

We believe that the present data do, in fact, represent fully developed (equilibrium) annular flows. This belief is chiefly based on examination of the adiabatic tube film flow data of Würtz (1978) obtained in test sections up to 9 m long. But also the annular geometry data reported by Moeck (1970) seem to support this our belief.

DISCUSSION OF RESULTS

Perhaps the most striking feature of the data presented in table 1 is that the tube film flow per unit perimeter is 2–5 times greater than the corresponding rod film flow. This pronounced asymmetry between the two films does not seem to be easily explained.

A deposition theory based on diffusion of droplets in a homogeneous gas core (e.g. James *et al.* 1979) cannot alone explain the asymmetry. The diffusion theory assumes that the entrained droplets interact with homogeneous gas core turbulence. The interactions are assumed to be such that the resultant path of the individual droplets resembles a random walk with a "small" mean free path. In the diffusion theory of deposition the droplets completely "forget" their origins.

If the interaction between the droplets and the turbulent gas core is very weak (in contrast to the assumption of diffusion theory) then the drops will move in approximately straight lines and the initial conditions will completely determine the subsequent paths. This "radiation theory" of deposition has some experimental foundation: recent results by Whalley *et al.* (1979) indicate that for air–water flow at about atmospheric pressure the larger droplets move in almost straight lines from the point of entrainment to the point of deposition. The larger droplets are principally responsible for the rate of deposition.

It is interesting to note that application of the classical radiation theory would not lead to a prediction of asymmetric conditions.

If we assume that the entrainment process is such that droplets are emitted according to Lambert's Cosine Law and that all droplets are absorbed upon impact with a film, then it follows from the classical theory of radiative exchange in enclosures (e.g. Howell *et al.* 1969) that

$$E_k - D_k = \sum_{j=1}^{2} (E_k - E_j)F_{k-j} \qquad [1]$$

Table 1. Results for steam–water experiments in a vertical 8-m long annular tests section. $D_{rod} = 17$ mm and $D_{tube} = 26$ mm

P MPa	G kg/m^2s	x %	-(dp/dz) kPa/m	$(W_F)_{Rod}$ kg/s	$(W_F/\Pi D)_{Rod}$ kg/s m	$(W_F)_{Tube}$ kg/s	$(W_F/\Pi D)_{Tube}$ kg/s m
3.0	500	20	7.6	0.0207	0.388	0.0762	0.933
3.0	500	40	14.0	0.0170	0.318	0.0486	0.595
3.0	500	50	17.2	0.0134	0.251	0.0354	0.433
3.0	1000	20	22.6	0.0310	0.580	0.1170	1.432
3.0	1000	40	34.8	0.0100	0.187	0.0316	0.387
5.0	500	40	9.3	0.0179	0.335	0.0559	0.684
5.0	1000	20	15.7	0.0331	0.620	0.1301	1.593
5.0	1000	40	24.3	0.0176	0.330	0.0483	0.591
5.0	1000	55	31.8	0.0070	0.131	0.0258	0.316
7.0	500	20	5.1	0.0199	0.373	0.0684	0.837
7.0	500	30	6.1	0.0167	0.313	0.0692	0.847
7.0	500	40	7.0	0.0170	0.318	0.0594	0.727
7.0	500	50	8.5	0.0141	0.264	0.0456	0.558
7.0	500	60	9.3	0.0132	0.247	0.0366	0.448
7.0	1000	20	12.1	0.0298	0.558	0.1404	1.719
7.0	1000	30	15.0	0.0249	0.466	0.0973	1.191
7.0	1000	40	17.4	0.0195	0.365	0.0565	0.692
7.0	1000	50	20.7	0.0103	0.193	0.0359	0.440
7.0	1000	60	23.7	0.0046	0.086	0.0240	0.294
7.0	2000	20	30.0	0.0334	0.625	0.1502	1.839
7.0	2000	28	36.1	0.0176	0.330	0.0833	1.020
7.0	2000	35	42.1	0.0073	0.137	0.0505	0.618
9.0	1000	20	10.2	0.0280	0.524	0.1271	1.556
9.0	1000	40	13.0	0.0170	0.318	0.0456	0.558

where $E(\mathrm{kg/m^2s})$ is the rate of entrainment (emission); $D(\mathrm{kg/m^2s})$ is the rate of deposition (absorption); F_{k-j} is the configuration (view) factor; and index 1 and 2 designate rod and tube respectively. Now, in the equilibrium situation we have that $E = D$ so that [1] becomes:

$$E_1 - E_2 = 0. \tag{2}$$

This equation says that the rate of entrainment from the rod and tube films are equal in the equilibrium situation. Therefore, the classical radiation theory of deposition, together with the assumption of emission of droplets, according to Lambert's Law, does not predict any asymmetry in deposition rates. For radiation theory to predict different rates of deposition for the rod and tube film the assumption of Lambert's Cosine Law must be dropped.

A complete theory for equilibrium annular flow in annular geometries must account not only for the deposition, but must also relate the entrainment rate to the film characteristics.

It seems that the only difference between the rod and tube films which might influence the entrainment process is the curvature of the gas–liquid interface. However, since the diameters of the rod and tube are orders of magnitude greater than both the film thicknesses and the diameter of the entrained droplets, it does not seem that this "curvature effect" can be responsible for the asymmetry.

A satisfactory explanation for the observed asymmetry between rod and tube film flows per unit perimeter may have to take into account the non-isotropy of gas core turbulence and the details of droplet–gas interactions.

CONCLUSIONS

The experimental results for film flow in fully developed (equilibrium) annular steam–water flows in an annular geometry were presented in table 1. The data indicate that the tube film flow rate per unit perimeter is 2–5 times greater than the corresponding rod film flow rate.

The diffusion theory for droplet deposition and a radiation theory based on Lambert's Cosine Law for deposition were discussed; it was found that neither theory predicts an asymmetry in the rod and tube deposition rates. It was considered unlikely that the difference between rod and tube film–gas curvatures is responsible for any appreciable difference between the entrainment rates from the two films.

It is finally speculated that an explanation of the observed asymmetry may be found in the non-isotropy of the gas core turbulence and the details of droplet–gas interactions.

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