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BRIEF COMMUNICATION

THE EFFECT OF SWIRL ON CRITICAL HEAT FLUX IN ANNULAR TWO-PHASE FLOW

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Abstract—The adaptation of a calculation method for critical heat flux using an annular flow model is described. If the swirl is assumed to deposit all the entrained drops onto the liquid film and to persist for a certain distance after the swirl device, good comparisons with experiment are obtained. A simple method for calculating the length over which the swirl persists is given.

1. INTRODUCTION

Bergles (1978) reviews the general topic of heat transfer enhancement and concludes that the introduction of devices introducing swirl in forced convection boiling in tubes can increase the critical heat flux significantly. The increases in critical heat flux are commonly in the range of 50–100%. When the critical heat flux is exceeded, the heat transfer performance deteriorates greatly, and so in a heat flux controlled situation—such as a nuclear reactor—the temperature of the heat transfer surface will increase rapidly. Thus any increase in the critical heat flux will allow greater safety margins, or operation at higher heat fluxes.

One of the most common methods of introducing swirl is by means of twisted metal tapes inserted along the tube length. The vapour–liquid mixture is thus forced to flow in a helical path. These twisted tapes usually run the whole length of the tube. This work examines the effect of short lengths of twisted tape in high quality flows where the flow pattern would be expected to be annular. In annular flow the liquid travels partly as a film along the tube walls and partly as small drops entrained into the vapour which flows along the centre of the tube. In water cooled nuclear reactor geometries, the critical heat flux can be increased by "mixing grids", which can be seen as, to some extent, analogous to short lengths of twisted tape inserted into the flow at intervals. Mixing grids have been described by, for example, Suchy *et al.* (1976). Of course mixing grids increase the pressure drop through the reactor, and so the pumping costs are also increased.

2. EXPERIMENTAL RESULTS

In a series of unpublished experiments, Bennett *et al.* (1967) have investigated the effect of short lengths of twisted tape on critical heat flux. The experiments were carried out in a vertical tube, 3.66 m long and 0.01262 m dia. The fluid was water at a pressure of 69 bar and a mass flux of 2712 kg/m^2 sec was used in all the experiments. The twisted tape insert and its dimensions are shown in figure 1. The twisted tape was mounted inside a bearing pad unit which is also shown in figure 1.

The critical heat flux for the tube was measured for various inlet subcoolings and was found to be very close to previously measured values. The critical heat flux was also measured with the bearing pads but not the twisted tape in the tube. The effect of the bearing pads was quite small; in most cases the critical heat flux varied by less than 5% from the value obtained in a plain tube. The critical heat flux is plotted against the inlet subcooling of the water for a plain tube in figure 2.

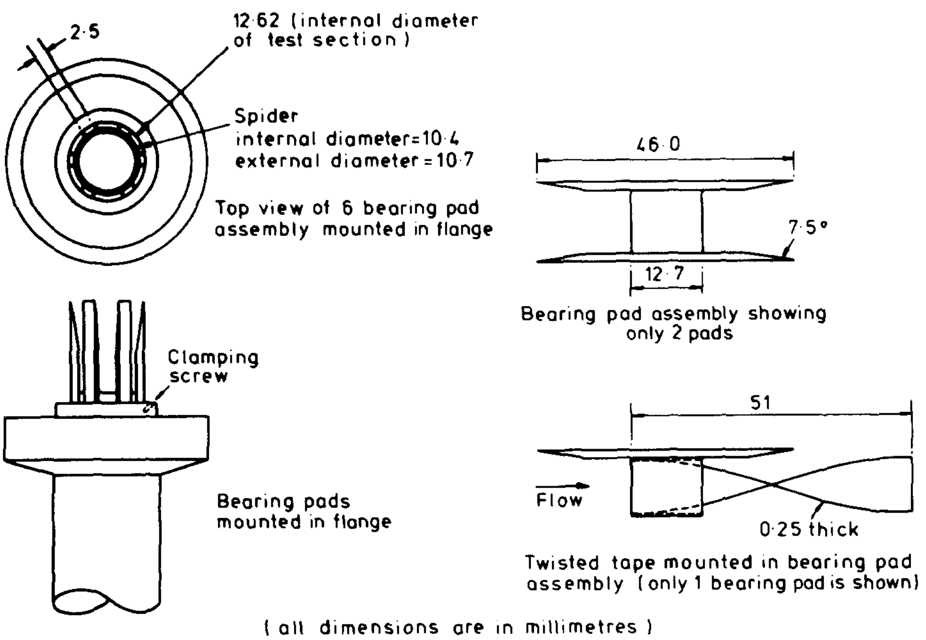

Figure 1. Swirl flow device used in experiments.

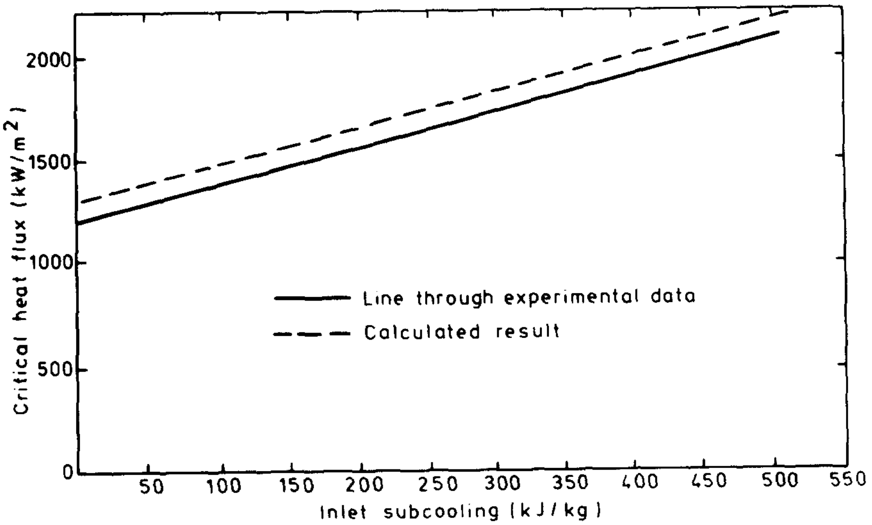

Figure 2. Comparison of experimental and calculated results for flow with no swirl.

When the twisted tape shown in figure 1 was used, increases in the critical heat flux of up to 25% on the plain tube value were obtained. The increase in critical heat flux was a strong function of the position of the twisted tape unit. Figure 3 shows the increase in critical heat flux obtained plotted against position of the unit. The significant details of the results were:

(1) The swirl unit has no effect when it is placed a long way from the top of the tube.

(2) As the swirl unit is moved towards the top of the tube, the critical heat flux increases and then falls again.

(3) The greatest rises in critical heat flux were obtained when the inlet subcooling of the water was lowest.

(4) When the swirl unit was near the top of the tube, the dryout occurred just below the swirl unit. In this case the critical heat flux was found to be equal to that for a tube length equal to the length from the tube inlet to the swirl unit. In other words, the swirl unit was not exerting any significant effect on the flow upstream of the unit.

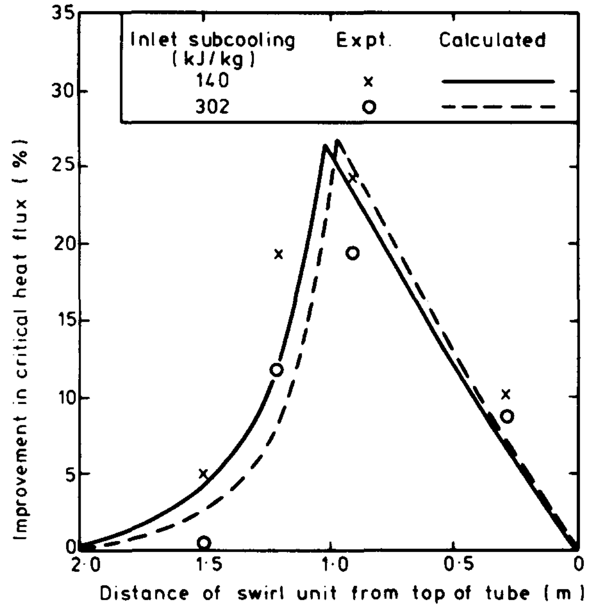

Figure 3. Calculated and experimental values for increase in critical heat flux as a function of swirl device position assuming swirl persists 0.5 m downstream of swirl device.

(5) When the swirl unit was not very near the top of the tube, the dryout occurred at the top of the tube.

3. CALCULATED RESULTS USING AN ANNULAR FLOW MODEL

Whalley *et al.* (1974) have described a method of calculating critical heat flux based on a mathematical model of annular flow. The flow rate in the liquid film on the walls of the tube is calculated, accounting separately for the effects of the evaporation of the film, deposition of liquid drops onto the film, and entrainment of liquid drops from the film into the gas core. Dryout is assumed to occur when the liquid film flow rate becomes equal to zero, and the critical heat flux is then the lowest value of the heat flux that will cause dryout to occur somewhere in the tube.

Figure 2 compares the experimental results for the plain tube (shown as a line drawn through the data points) and the calculated results. The calculated results are about 6% too high.

3.1 *Probable effects of the swirl flow device*

The swirl flow device will impose a rotating motion on the flow. This will cause the liquid drops in the vapour flow to undergo a larger deposition rate than usual because of the action of centrifugal forces on the drops. There may also be a tendency for large drops to be entrained into the vapour flow from the end of the twisted tape. As a first approximation it was assumed that the swirl caused all the droplets to be deposited, and so after the swirl device the film flow rate was assumed to be equal to the total liquid flow rate at that point.

3.2 *Persistence of the swirl in the flow*

The swirl will persist in the vapour flow for some distance after the end of the twisted tape. The swirl will gradually decay, but here, to obtain an estimate of the persistence, the time constant for decay of the swirl is calculated.

If a thin disk of the flow is considered, thickness δz and radius, R equal to the radius of the tube, then the rate of change of angular velocity, ω is given by

$$2\pi R^2 \tau_c \delta z = -I \frac{\mathrm{d}\omega}{\mathrm{d}t} \qquad [1]$$

where t = time, I = moment of inertia of the disk about an axis through the centre of the disk in the z direction, τ_c = shear stress at the edges of the disk in the circumferential direction. For a disk

$$I = \delta M \frac{R^2}{2} \qquad [2]$$

where δM = mass of the disk, which is given by $\delta M = \pi R^2 \rho \delta z$, where ρ = density of the material in the flow. From [1] and [2]

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = -\frac{4\tau_c}{\rho R^2}. \qquad [3]$$

The time, t_0 for the swirl to decay is now estimated roughly. In order to do this, some estimate must be used for the circumferential shear stress, τ_c. It can be argued that the absolute fluid velocity, U above the swirl device can be resolved into two components: U_a in the axial direction and U_c in the circumferential direction (see figure 4). Then the shear stress can be calculated from a Fanning friction factor, c_f and the absolute velocity

$$\tau = \tfrac{1}{2}\rho U^2 c_f. \qquad [4]$$

This shear stress along the velocity vector can then be resolved into an axial component, τ_a and a circumferential component τ_c. Thus τ_c is given by

$$\tau_c = \tau \cos \alpha \qquad [5]$$

where α is defined in figure 4, thus

$$\cos \alpha = \frac{U_c}{U} \qquad [6]$$

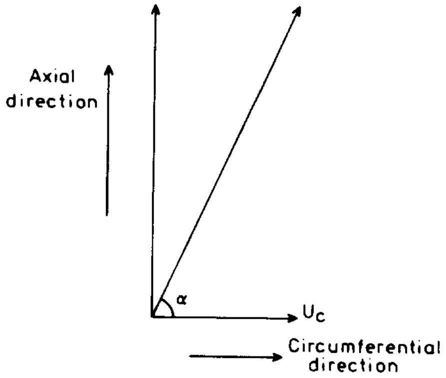

Figure 4. Components of velocity after the swirl flow device.

and so from [4]–[6]

$$\tau_c = \tfrac{1}{2}\rho U U_c c_f. \qquad [7]$$

The circumferential velocity, U_c of the fluid near the tube wall is

$$U_c = R\omega \qquad [8]$$

and therefore

$$\tau_c = \tfrac{1}{2}\rho U R\omega c_f. \qquad [9]$$

Substituting this equation for τ_c into [3]:

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = -\omega\left(\frac{2c_f U}{R}\right). \qquad [10]$$

The angular velocity thus decays exponentially, and the time constant, t_0 is

$$t_0 = \frac{R}{2c_f U}. \qquad [11]$$

This distance travelled by the axial flow, z_0 in this time is

$$z_0 = U_a t_0. \qquad [12]$$

For the experiments being analysed here U_c/U_a is typically less than 0.4, and so $U_a/U > 0.9$. Therefore U in [11] can be replaced by U_a with little loss of accuracy, and then combining [11] and [12]:

$$z_0 = \frac{R}{2c_f}. \qquad [13]$$

Hence a convenient result is obtained; the swirl persists for a length which is dependent on the density and velocity of the flow only in as much as the friction factor depends on these variables. In this case, the following values were taken for the variables in [13]

$R = 0.00631$ m (the tube radius)

$c_f = 0.005.$

The friction factor value was taken as a resonably high value (so as to take some account of the extra shear stress caused by the liquid film) for a smooth tube at a Reynolds number of 0.5×10^6. This is the Reynolds number for the vapour flowing alone at a quality of about 30%, and 30% was a typical quality at the swirl device. The friction factor was taken as a constant because of the considerable uncertainties about its actual value. Substituting the above values in [13], $z_0 = 0.63$ m.

This rough estimate therefore suggests that the swirl will persist for about 0.63 m after the swirl device, and is consistent with common engineering practice that disturbances persist for about 50 diameters along the tube.

3.3 *Calculated results*

The critical heat flux was calculated using the method described at the beginning of section 3 for the swirl flow. The assumptions made about the effect of the swirl were (i) the swirl device deposits all the entrained drops onto the film, and (ii) the liquid film flow rate remains equal to the total liquid flow rate until a distance z_0 after the swirl device. The experimental and calculated results are plotted in figure 3 for $z_0 = 0.5$ m: this was the value of z_0 which gave the best agreement between experimental and calculated results. The percentage increase in critical heat flux is defined in terms of two experimental results (with and without swirl device) for the experimental data points, and in terms of two calculated results for the calculated lines. The percentage increase is plotted against the distance of the swirl device from the end of the tube.

3.4 *Comparison with experiment*

From figure 3 it can be seen that the general trend of the experimental results is reproduced by the calculations. The increase in the critical heat flux is of the right magnitude, and the dependence upon swirl device position is also correctly calculated. The dependence of the increase in critical heat flux upon inlet subcooling is correctly predicted when the swirl device is some distance from the top of the tube, but not correctly when it is close to the top of the tube.

A value of z_0 of 0.5 m (used in figure 3) gives better results than the value of 0.63 m calculated in section 3.2. In view of the considerable uncertainty in calculating z_0, this discrepancy is not surprising.

The calculations also give information on the position of dryout, and this is indicated in figure 5. When the swirl device is near the top of the tube, dryout occurs just upstream of the swirl device; when the swirl device is further from the end of the tube, dryout occurs at the top of the tube. The abrupt change in slope of the calculated line in figures 3 and 5 occurs where the dryout changes from one position to another; to the left of the peak is the region considered in this paper, to the right of the situation is simply that of a short heated tube. In as far as experimental information is available, these calculations of dryout position are substantiated.

4. CONCLUSIONS

It has been shown that the behaviour of critical heat flux for flow with a swirl device can be predicted by means of an annular flow calculation method. Two simple assumptions are necessary

(1) The swirl device causes all the liquid drops in the vapour core to be deposited on the liquid film.

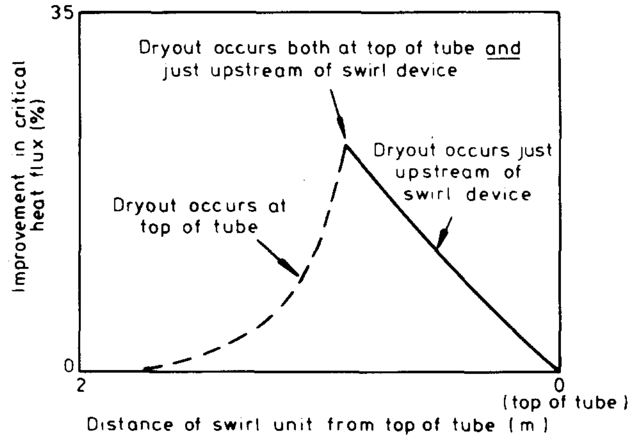

Figure 5. Dryout position in calculated results.

(2) The swirl persists, and continuous to have this effect, for a distance z_0.

This distance z_0 has been estimated by a crude method, and a value in the region of that calculated by this method has been shown to lead to good overall for critical heat flux.

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