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MEASUREMENT OF VOID FRACTION IN STEADY-STATE SUBCOOLED AND LOW QUALITY FLOW FILM BOILING

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INTRODUCTION

Subcooled and low quality flow film boiling are heat transfer modes commonly encountered during the reflooding phase of a loss-of-coolant accident of a nuclear reactor. The flow regime in this heat transfer mode is either inverted annular or dispersed flow, depending on the local void fraction. High degrees of thermal non-equilibrium can be present because of vapour superheat (the heated surface temperature is well beyond the Leidenfrost temperature) and/or liquid subcooling being present during film boiling. Prediction of the void fraction in the inverted annular flow regime requires assumptions regarding slip ratio, vapour superheat and liquid subcooling; in many cases predictions can vary anywhere from 1 to 95 per cent void fraction.

The present study was carried out to improve our understanding of the inverted annular flow regime. Direct measurements of void fraction were made using a γ-ray attenuation technique. The measurements were obtained during steady-state film boiling of water at atmospheric pressure flowing vertically upwards inside a directly heated tube.

EXPERIMENT

The experimental setup (shown in figure 1) has been reported elsewhere (Groeneveld & Gardiner 1978). It employs the hot patch technique to establish film boiling inside a tube with water as coolant. In the present investigation, a γ-densitometer is used to measure the void fraction along the test section. The dimensions of the test section and the relative positions of the source, test section and detector are shown in figure 2. The source (50 mCi cesium-137) is encased in a collimator which, together with the detector, can be moved parallel to the tube axis to measure the attenuation at different axial locations. The densitometer is calibrated using cylindrical plexiglass inserts of different diameter to simulate inverted annular flow. Good agreement was obtained between measured and predicted attenuation. Figure 2 also shows that the calculated attenuation in an inverted annular flow regime is almost identical to that of a homogeneous flow regime for our particular configuration. The difference is much smaller than the random error, hence our assumption that the void fraction depends only on the attenuation, regardless of phase distribution is justified. In the actual void measurement, the standard deviation due to the statistical fluctuation of the radioactive decay process is calculated to be 3 per cent of void fraction.

RESULTS AND DISCUSSIONS

The void fractions are measured at mass fluxes of 400 and 500 $\mathrm{kg \cdot m^{-2} \cdot s^{-1}}$ and various subcoolings, heat flux levels and axial locations. Some of the data are plotted in figure 3 as

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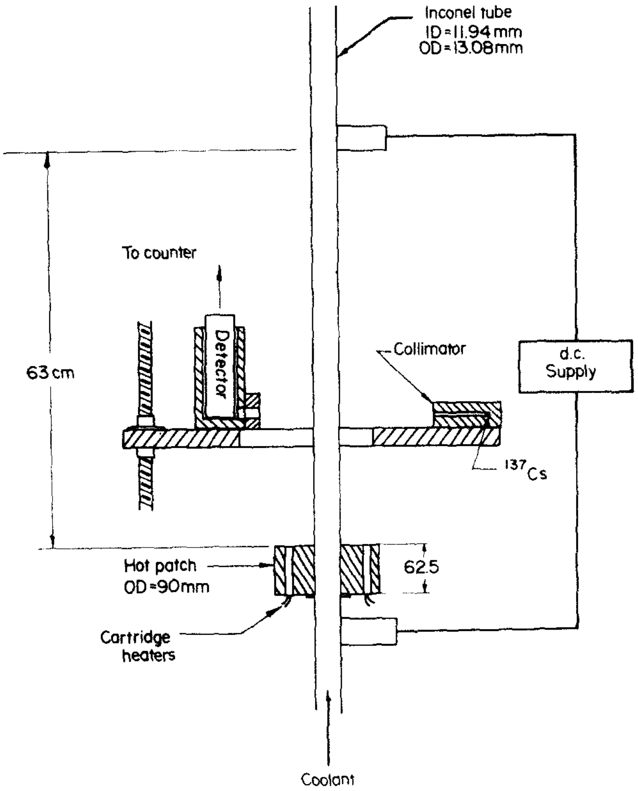

Figure 1. Schematic of test section and γ-densitometer.

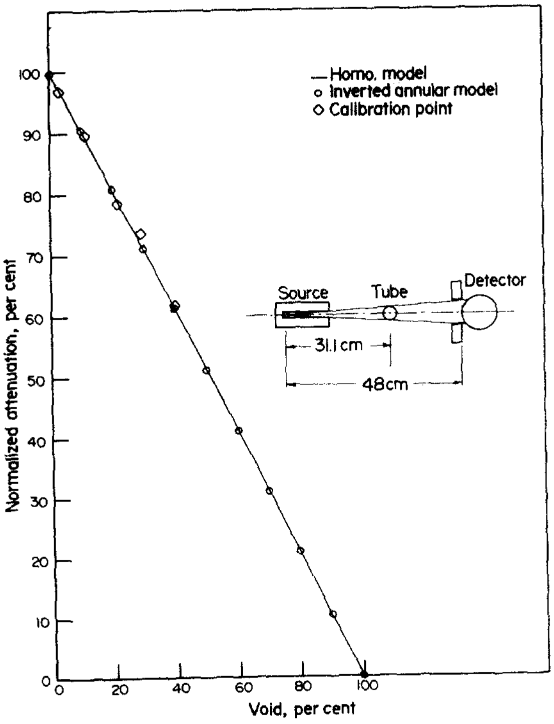

Figure 2. Gamma densitometer calibration.

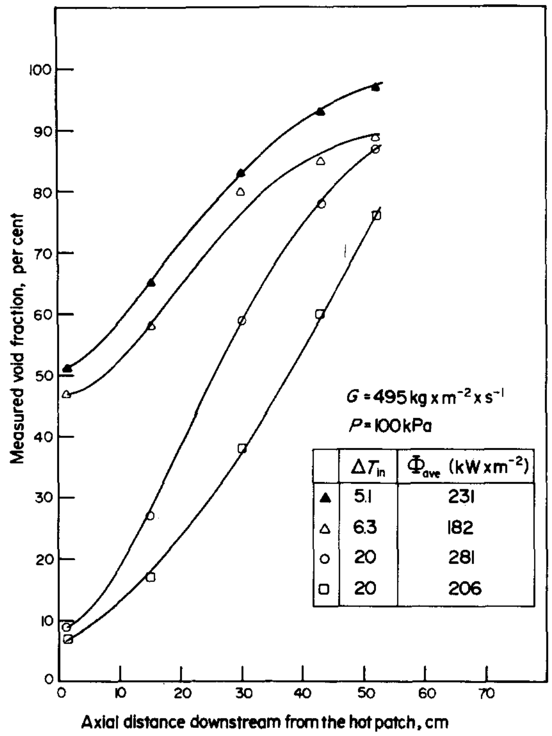

Figure 3. Axial variation of void fraction.

measured void fraction vs axial location. It can be seen that the void fraction at a fixed axial location increases with a decrease in inlet subcooling and an increase in heat flux. When the data are replotted in figure 4 against equilibrium quality† these effects can no longer be discerned. This suggests that the local phase and velocity distribution is primarily a function of equilibrium quality.

Inside the hot patch the flow regime will be inverted annular when film boiling is first established. The distance over which this flow regime is maintained depends on the void fraction. Plummer (1974) suggested that at a void fraction of approx. 40 per cent the inverted annular flow regime changes into dispersed flow. It can be seen from figure 4 that the void fraction is in the neighbourhood of 50 per cent at zero equilibrium quality. This would suggest that most of the data in the net equilibrium quality region are in the dispersed flow regime.

In figure 5 the calculated void fraction, $\alpha = X/[X + \rho_v/\rho_L \cdot S \cdot (1 - X)]$, based on constant slip and either saturated or film temperature for the vapour, is compared to the data measured during a low inlet subcooling test. In calculating the void fraction it is assumed that the liquid has reached saturation before the first measurement station (located 5 cm downstream of the hot patch). This assumption is reasonable since the coolant is only slightly subcooled at the test section inlet. The predictions show that high slip ratios tend to lower the predicted void fraction, while higher vapour superheats affect the void fraction either way through a decrease both in quality and vapour density (the cross section average enthalpy remains constant). For the condition of figure 5 an increase in vapour superheat increases the void fraction.

Figure 5 also shows the axial surface temperature profile downstream from the hot patch. The lower surface temperature near the hot patch is due to locally enhanced heat transfer which was discussed in detail in a previous paper (Fung 1979). The surface heat flux along the test section length varies slightly due to a change in the resistance coefficient (±3 per cent); at the hot patch the surface heat flux is 10–40 percent higher.

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†Equilibrium quality is defined here as $(h - h_{Lsat}/h_{fg})$ where h is the cross-sectional average fluid enthalpy evaluated from a heat balance.

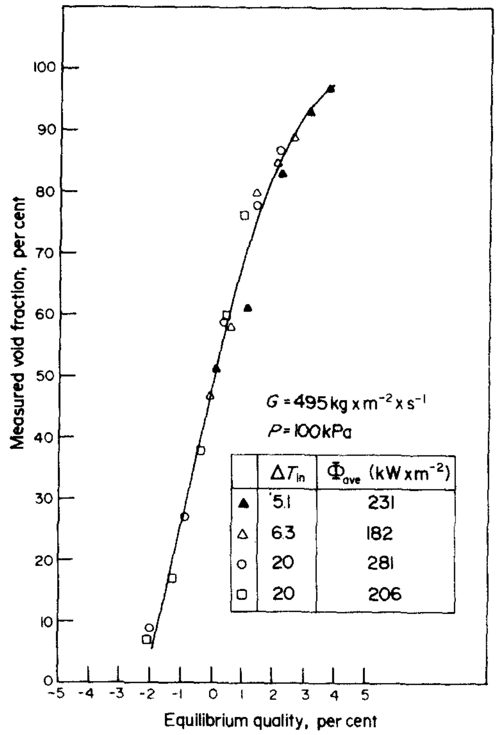

Figure 4. Void fraction as a function of equilibrium quality.

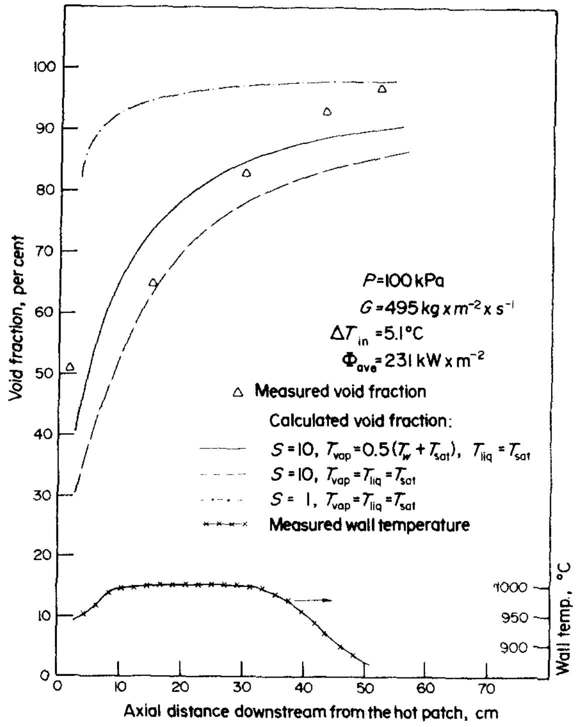

Figure 5. Comparison of measured void with prediction.

Figure 5 shows that a no slip assumption results in a large over-prediction of void fraction just downstream from the hot patch. Hence high slip velocities must have developed inside the hot patch. Also, near the start of the film boiling region the measured axial gradient in void fraction is lower than any of the predictions. This may be explained by (i) an increase in slip ratio, or (ii) a combination of increase in slip ratio and decrease in vapour superheat. In dispersed flow a decrease in vapour superheat is unlikely to take place. Thus, with an increase in void an increase in slip ratio is more probable.

Further downstream the axial void fraction gradient becomes larger than any of the predictions. This is to be expected as the flow regime will be dispersed and the liquid core will have broken up into small droplets. Predictions from post-CHF models (e.g. Groeneveld 1976) have shown that smaller droplets are more likely to be accelerated, thus reducing the slip ratio and hence increasing the axial void fraction gradient above the constant slip ratio predictions of figure 5.

CONCLUSION

Void fraction during subcooled film boiling of water inside a tube has been successfully measured by means of a γ-attenuation technique. The results suggest that, at near atmospheric pressure, inverted annular flow only exists under thermodynamic subcooled conditions. In the net quality region, the flow is dispersed.

The data also show that at atmospheric pressure and a fixed mass flux the void fraction can be correlated successfully by the equilibrium quality.

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NOMENCLATURE

G	mass flux
h	enthalpy
h_{fg}	latent heat
P	pressure
S	slip ratio
T	temperature
ΔT_{in}	inlet subcooling
X	quality
α	void fraction
ρ	density
ϕ_{ave}	surface heat flux (averaged over test section length downstream of the hot patch)

Subscripts

liq, l	liquid
sat	saturated
vap, v	vapour
w	wall

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