TRANSIENT ANALYSIS OF BOILING TRANSITION PHENOMENA USING LIQUID FILM FLOW MODEL

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Boiling water reactor (BWR) cores have to be designed so as to prevent boiling transition (B.T.) during any transient. If B.T. occurs, a liquid film flow along a fuel rod disappears and its wall temperature rises. When power decreases or flow rate increases after B.T., the wall rewets with the liquid film, and the temperature decreases. If this rewet takes place fast enough, fuel damage could be prevented. Therefore the analysis of phenomena after B.T. is important in order to estimate the true thermal margin of the core design.

To predict B.T. without using experimental correlations, subchannel methods with liquid film flow model have been studied(1)~(3). Tomiyama et al.(2) developed a B.T. prediction program SILFEED by coupling a subchannel method and Whalley’s liquid film model(3). The SILFEED predicted steady state B.T. power in BWR bundles very well. However, for the purpose of the above examination, the method is required to have a mist flow cooling model and a rewetting model. It is also desirable that the computing time is very small to be solved for studying on a core design.

In order to satisfy such requirements, a new transient single subchannel model which has a liquid film dryout model, a mist flow cooling model and a rewetting model, has been developed. In this note, the details of the model and some examinations are described.

1. Single Subchannel Model

According to full scale experiments, the hottest subchannel locations in steady and transient states were almost the same(4). Therefore only the hottest subchannel is analyzed here. The hottest subchannel location is determined with steady state subchannel analysis. To apply a single subchannel program to the hottest subchannel, power and flow rate of the subchannel are needed. The power can be estimated with fuel-rod power facing to the hottest channel. While, the flow rate was estimated by

$$G_{\text{HOT}} = f_{\text{HOT}} \cdot G,$$

where $G_{\text{HOT}}$ and $G$ are the mass flux of the hottest subchannel and the bundle and $f_{\text{HOT}}$ is the correction factor for the flow into the hottest subchannel. The factor $f_{\text{HOT}}$ was calculated with the subchannel analysis. The example analytical results is shown in Fig. 1. The factor $f_{\text{HOT}}$ is dependent on the local rod peaking and geometry, but dependence on the average flow rate or the power of the bundle are small. Therefore $f_{\text{HOT}}$ is supposed to be constant, even if the flow and the power of the bundle are changed.

2. Analytical Model

When B.T. occurs, the flow pattern changes from annular to mist flow. When rewetting occurs, it returns from mist flow to annular flow. In order to simulate B.T. and rewetting, it is necessary to switch between annular flow and mist flow calculations. Therefore the present program consists of annular and mist flow subroutines. On disappearing or reforming of the film, calculation is switched from one to the other subroutine.

(1) Annular Model

Whalley’s film model(3) has been extended. In Whalley’s model, gas temperature is considered to be saturated. But if B.T. occurs upstream, gas may be superheated. Therefore...
the heat transfer between gas and droplets and between the gas and the film have been taken into account. The temperatures of the droplets and film are assumed to be saturated. The basic equations are represented as follows:

Continuity equation for the liquid film:
\[
\frac{\partial}{\partial t}(\alpha_F \rho_L) + \frac{\partial}{\partial z} G_F = D - E - B_{WF} - B_{GF},
\]

Energy equation:
\[
\frac{\partial}{\partial t}(\alpha_F \rho_L h_0 + \alpha_F \rho_L h_L + \alpha_F \rho_L h_L - P) + \frac{\partial}{\partial z}(G_0 h_0 + G_D h_L - G_F h_L) = \Phi.
\]

The present method has been coupled with a transient program PARADYN\(^{(5)}\) for boundary condition calculation. Results from PARADYN are used as follows:

\[
G_0 + G_D + G_F = G(t).
\]

That is, PARADYN calculates total mass flux \(G(t)\) of each axial node, and the present method calculates the distribution of gas, film and droplets from \(G(t)\).

Transition conditions are represented as follows:

B. T. condition; \(\alpha_F \leq 0.0\).

Rewetting condition; \(\alpha_F > 0.0\).

The latter condition can be rewritten by using Eq. (2) as follows:

\[
\frac{\partial}{\partial t}(\alpha_F \rho_L) = D - E - B_{WF} - B_{GF} - \frac{\partial}{\partial z} G_F > 0.0.
\]

Under mist flow condition, evaporation \(B_{WF}\) in Eq. (7) can not be defined, because liquid film does not exist. However, contact of droplets on hot wall or progress of liquid film front, induces evaporation \(B_{WF}\). Hence, \(B_{WF}\) is calculated by

\[
B_{WF} = \frac{4q_{WF}}{D_H H_{FG}},
\]

\[
q_{WF} = h_{WF}(T_F - T_S),
\]

where \(h_{WF}\) is the boiling heat transfer coefficient, and \(T_F\) and \(T_S\) are temperatures of the fuel rod wall and the liquid film.

(2) Mist Flow Model

The gas of mist flow may be superheated, so the heat transfer between the wall and the gas, between the gas and the droplets, and between the droplets and the wall has been accounted for. The basic equations for mist flow are expressed as follows:

Continuity equation for the entrained droplets:
\[
\frac{\partial}{\partial t}(\alpha_D \rho_D) + \frac{\partial}{\partial z} G_D = - B_{GD} - B_{WD},
\]

Energy equation:
\[
\frac{\partial}{\partial t}(\alpha_D \rho_D h_0 + \alpha_D \rho_D h_L - P) + \frac{\partial}{\partial z}(G_0 h_0 + G_D h_L) = \Phi.
\]
Information of transient program PARADYN:

\[ G_a + G_d = G(t). \]  

(12)

And the convection heat transfer models, which were used here, are Jens-Lottes correlation for wall-film heat transfer, Dougall-Rohsenow correlation for wall-gas heat transfer, Dittus-Boelter correlation for film-gas heat transfer, and Ross-Hoffman correlation for droplet-gas heat transfer.

3. Analytical Results and Discussions

Steady state and transient B. T. experiments of a BWR mockup fuel bundle were carried out in Hitachi Core and Fuel Thermohydraulic Test loop (HICOF). The flow area of HICOF bundle was divided into subchannels as shown in Fig. 1. The hottest channel location was 6th subchannel according to both of steady state subchannel analyses and experiments. This 6th subchannel was analyzed using flow factor \( f_{\text{HOT}} = 0.97 \) in Fig. 1. Figure 2 shows the comparison of calculated and measured steady state B. T. powers. They agreed to within \( \pm 3.8\% \). Single subchannel model appears to be an effective method to predict B. T. power. However, B. T. onset points of the experiments differed from the analyses. According to the experimental observations, B. T. occurred upstream of 1st or 2nd spacer. While, the present program predicted the 1st spacer B. T. only. The reason may be that the effect of spacers to film flow is not implemented in the program. Therefore, the present program calculates the film thickness upstream of the 1st spacer well, but the thickness at the 2nd spacer may be inaccurate.

Next, transient experiments were analyzed. In this note one result of these analysis is reported. Another results are almost the same as this one. Figure 3 shows the transition of flow and power. The power was changed rapidly, while the channel flow was decreased gradually.

The analytical changes of the film thickness along fuel rod are shown in Fig. 4. The film thickness monotonously decreased along axial position due to evaporation from the liquid film. After 4.5 s, the film thickness decreased due to increase in heat flux from fuel rods. At 5.5 s dryout occurred near to the top of bundle, and dryout region spread upward quickly. But after that, the dryout region became narrow due to heat flux decrease. At 7.4 s the dryout region disappeared, the rod surface was covered by the film flow, that is to say, rewetting occurred.
By the way, in order to measure the wall temperature of fuel rod, thermocouples were installed upstream of 1st and 2nd spacers in the experiment. The comparison of the measured and the analytical wall temperatures are shown in Fig. 5(a) and (b). Figure 5(a) is result for 1st spacer location, and Fig. 5(b), for 2nd spacer location. According to the experimental results of Fig. 5(a), dryout occurred at 5.50 s and fuel rod rewetted at 7.26 s. While the single subchannel program predicted that B.T. and rewetting times were 5.50 and 7.20 s. The analytical and the experimental onsets agreed to within 0.2 s. While the results of Fig. 5(b) differed from Fig. 5(a).

![Fig. 5 Wall temperature at 1st and 2nd spacers](image)

4. Conclusions

A new transient subchannel model which has liquid film dryout model, mist cooling model and rewetting model, has been developed in order to predict boiling transition and rewetting in BWR bundle. The new program has been applied to steady state and transient analyses in BWR bundle of HICOF loop. The results are summarized as follows:

(1) The calculated and the measured steady state B.T. powers agreed to within ±3.8%. However, B.T. onset point of experiment differed from analysis. According to the experimental observations, B.T. occurred upstream of 1st or 2nd spacer. While, the present program predicted, 1st spacer only. It may be that the effect of spacers to film flow is not implemented in the present program.

(2) The onsets time of B.T. and rewetting at 1st spacer were predicted within 0.2 s error. However the onset of rewetting at 2nd spacer predicted late. Because the film thickness at 2nd spacer was calculated in excess.

**[NOMENCLATURE]**

- \( B_{GD} \): Evaporation by heat transfer between gas and droplets (kg/m\(^3\)s)
- \( B_{GF} \): Evaporation by heat transfer between gas and liquid film (kg/m\(^3\)s)
- \( B_{WD} \): Evaporation by direct contact heat transfer (kg/m\(^3\)s)
- \( B_{WF} \): Evaporation by heat transfer between wall and liquid film (kg/m\(^3\)s)
- \( C \): Homogeneous droplet concentration (kg/m\(^3\))
- \( D \): Deposition rate of droplets (kg/m\(^3\)s)
- \( D_H \): Equivalent diameter (m)
- \( d_B \): Droplet diameter (m)
- \( E \): Entrainment rate of droplets (kg/m\(^3\)s)
- \( G \): Mass flux (kg/m\(^2\)s)
- \( H_{FG} \): Latent heat (J/kg)
- \( h \): Enthalpy (J/kg)
- \( P \): Pressure (Pa)
- \( m \): Film thickness (m)
- \( N \): Droplet number density (1/m\(^3\))
- \( T_F \): Fuel rod wall temperature (°C)
- \( t \): Time (s)
- \( u \): Velocity (m/s)
- \( Z \): Axial position along rod (m)
- \( a \): Volumetric fraction
\[ \lambda: \text{Thermal conductivity} \quad (\text{W/m}^2\cdot\text{K}) \]
\[ \mu: \text{Viscosity} \quad (\text{kg/ms}) \]
\[ \rho: \text{Density} \quad (\text{kg/m}^3) \]
\[ \sigma: \text{Surface tension} \quad (\text{N/m}) \]
\[ \Phi: \text{Heat generation rate per unit volume} \quad (\text{W/m}^3) \]

(Subscripts)

- REFERENCES -