Independent Verification of Effects of Spacer Grids during Reflood Phase for Implementation into SPACE code

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1. Introduction

Understanding the mechanisms of a quenching of hot fuel rods is important for the analysis of the reflood phase immediately after a postulated loss-of coolant accident (LOCA). [1] At short times, they should strongly experience a dispersed two-phase droplet flow, flow blockage plays an important role in heat transfer augmentation during reflood. It is largely due to flow boundary redistribution and an interfacial area increase primarily attributed to a breakup by impinging drops in presence of obstacles like spacer grids or local clad swelling, etc. Few studies, however, have numerically demonstrated significant effects of spacer grids as one of flow blockage.

In this paper, we will discuss effects of spacer grids on a heat transfer enhancement and drop break-up and propose key models to the implementing into SPACE (Safety and Performance Analysis Code for Nuclear Power Plant) code.

2. Effects of Spacer Grids

The spacer grid is a structure to support the nuclear fuel rods laterally and vertically with a friction grip. The grid quenching, which can occur because the grids are unpowered, causes creation of additional liquid surface area. It makes the vapor phase de-superheated due to a higher interfacial heat transfer coefficient of a wetted portion than a drop. The liquid film is easy to evaporate, which results in an enhancement of convective heat transfer and a higher steam flow. In addition to grid rewet, the entrained drop can be shattered into smaller drop. Smaller droplets have an advantage over evaporation because of high surface to volume ratio, so it gets to the additional steam source to increase the convective heat transfer coefficient. The grid models implemented into COBRA-TF are referenced, because those models of which have good validation with FLECHT SEASET data. [2]

2.1 Single phase heat transfer enhancement

The coolant flow should experiences decelerate and accelerate past a spacer grid, which causes an increase of turbulence and results in local enhancement of heat transfer. Regarding this, Yao, Hochreiter and Rich (1982) published a simple correlation in Eq. (1)

$$\frac{Nu_X}{Nu_O} = 1 + 5.55\ a_r^2 \exp(-0.13\ x/D_h) \qquad (1)$$

Where x is distance from upstream grid and D_h is hydraulic diameter. It can be used for Re>10^{-4} and $0.256 < a_r < 0.348$ (the blockage ratio). So, it depends only on the geometry.

2.2 Rewet model

In order to determine the quench front, a simple two region model is introduced in Fig. 1. Wet region is below the grid quench front. The liquid film has saturated temperature. Dry region is above quench front and has the grid temperature close to the rod temperature.

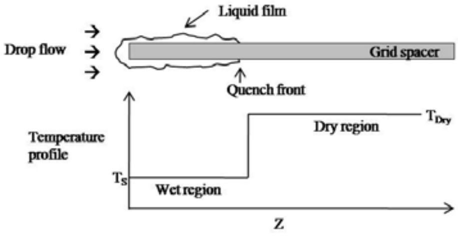

Fig. 1. A conceptual model of the quench front and rewet

2.2.1 Dry region heat balance

The heat balance is used to determine the grid dry temperature. Heat flux from heated rods and vapor is balanced with convective heat flux to vapor and drop contact heat transfer.

$$\frac{P_G}{A_C}\left(q_{rad}''' - q_{conv}''' - q_{dcht}'''\right) = \rho C_P \frac{\Delta T_G}{\Delta t} \qquad (2)$$

Where, P_G grid perimeter, A_C half cross sectional area, ρ drop density, C_P specific heat, T_G is dry grid temperature.

2.2.2 Wet region heat balance

In the similar manner, heat balance in wet region is used to determine temperature of wet portion.

The liquid film will recede if the liquid deposition rate is less than the entrain rate. So, mass flux of drop contact heat transfer for wet portion is defined as

$$\dot{m}_{DE} \rangle \dot{m}_{EVAP}, \qquad \dot{m}_{DE} = \left(\frac{A_G}{A_C}\right)\dot{m}_E \qquad (3)$$

The entire drops flowing within the projected area of grid (A_G) are assumed to be captured. (A_C = flow channel area, m_E = the entrained liquid flow rate)

2.2.3 Quench front model

The quench front velocity model is well-described by two-region analytical conduction solution of Yamanouchi (1968).

$$V_Q = \left\{ \frac{\rho_G C_{P_G}}{2} \left(\frac{\delta}{h_w k_g}\right)^{1/2} \left[\left(1 + 2\frac{T_G - T_W}{T_W - T_f}\right)^2 - 1 \right]^{1/2} \right\}^{-1} \qquad (4)$$

Here, the heat flux at a quench front, h_w, and rewet temperature, T_w, are adjustable parameters. The value of h_w is determined by Zuber pool boiling critical heat flux correlation and T_w is recommended 500 $^\circ F$ in COBRA-TF. [2]

2.3 Drop break-up and interfacial area between drops and vapor

The grid strap thickness (about 0.3 mm) is relatively thin compared to the drop diameter (about 1.3 mm), which results in the entrained drop shattering. The mass flux of smaller drops is defined by the grid blockage ratio and efficiency factor of grid.

$$\dot{m}_{DB} = \eta_e \left(\frac{A_G}{A_C} \right) \dot{m}_e \qquad (5)$$

To complete drop break-up model, an expression for a characteristic diameter of shattered drops is needed. It can be based on Weber number defined by features of impacting drops.

$$We_D = \frac{\rho_d V_{DI}^2 D_I}{\sigma} \qquad (6)$$

Where, V_{DI} is velocity of impacting drops and D_I is diameter of impacting drop.

The model for effects of spacer grids are summarized in Table I.

Table I: Key models for effects of spacer grids

	Models	Remarks
Single phase heat transfer enhancement	$\frac{Nu_X}{Nu_O} = 1 + 5.55\ a_r^2 \exp(-0.13\ x/D_h)$	Vapor phase heat transfer enhancement by flow redistribution
Rewet model	$H_{GRID} = \frac{k_\ell}{D_H}(0.023\mathrm{Re}_v^{0.8}\ \mathrm{Pr}_v^{0.3})0.222P_W$	Interfacial (vapor - drop) HTC enhancement by quenching
	$Q_{vapl} = q''_{conv} \cdot N_G \cdot P_G \cdot L_{G,D}$	Heat flux from dry region of spacer grids to vapor field
Drop Break-up	$\dot{m}_{DB} = \eta_e \left(\frac{A_G}{A_C} \right) \dot{m}_e$ $S'''_{grid} = (1-\xi)\ \dot{m}_{DB}$	Interfacial area (drop-vapor) change by drop break-up due to spacer grids

2.4 brief talk about interfacial area transport equation for drop fields

During reflood, effects of the entrained liquid drops become important. The interfacial area concentration transport equation about entrained liquids should be needed to precisely simulate the interfacial transport phenomena during the transient and in-between flow regimes. [3, 4]

$$\frac{\partial A_i'''}{\partial t} + \nabla \cdot \left(A_i''' \overline{U}_e \right) = A'''_{i,E} + A'''_\Gamma + A'''_{grid} \ , \quad A'''_{i,E} = \frac{3S'''}{\rho_d r_s} \qquad (7)$$

Especially, A'''_Γ is rate of interfacial area concentration change due to phase change and A'''_{grid} is taken to be appropriate correlation by drop break-up effect as explained in section 2.3.

3. Verification Test

Independent verification of spacer grids effects are carried out in a number of example conditions.

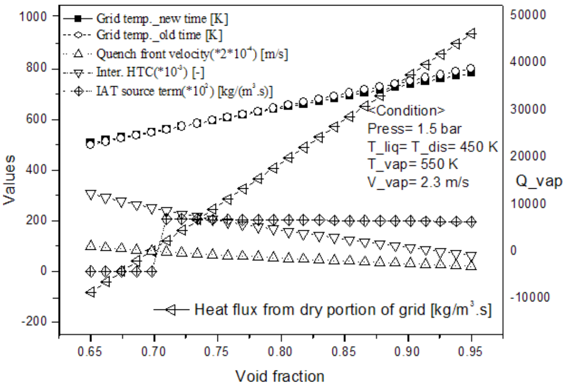

Fig. 2. Independent verification of models for spacer grids effects in case of a number of example conditions.

As stated in figure 2, models of spacer grids effects have worked well. Based on this, it is in progress to implement the effects of spacer grids and interfacial area transport equation into SPACE code which already adopted three-dimensional, transient, two phase and three-field model (gas, continuous liquids and entrained liquids). [5]

4. Conclusions

In this work, independent verification to implement models for effects of spacer grids during reflood phase into the SPACE code are presented. In this situation, models for spacer grids of COBRA-TF are referenced. It is in progress to implement the effects of spacer grids and interfacial area transport equation into SPACE code. This implementation will be very powerful to intensely understand nature of physics that fuel rods undergoes during the reflood phase.

Acknowledgment

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