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Incorporation of Droplet Breakup Model at Spacer Grid into RELAP5/MOD2

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핵연료봉 지지격자에 의한 Droplet Breakup Model의 RELAP5/MOD2 삽입

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Abstract

Recent experiments show the existence of spacer grid improves the heat removal from the fuel rods during the reflood phase of LOCA. The local heat transfer within and downstream of the grid is increased due to the earlier quenching than rod surface, shattering of the entrained droplets into smaller ones which can be more easily evaporated and enhanced turbulent effect. Therefore, the consideration of these phenomena is necessary for the DFFB regime which prevails above the water level during the reflood. In this paper, droplet breakup model at spacer grid has been developed and incorporated into RELAP5/MOD2. Verification calculations are carried out for FEBA tests which examine the thermalhydraulic performance of grid spacer during reflood.

요 약

최근 수행된 일련의 실험들을 통하여 핵연료 집합체 지지격자(Spacer Grid)의 존재가 냉각재상실사고시에 핵연료봉으로부터의 열제거에 긍정적인 효과를 미치고 있음이 밝혀졌다. 그 이유는 열원이 없는 지지격자가 연료봉보다 먼저 퀜칭이 일어나며 물방울이 지지격자에 부딪쳐서 잘게 부수어져 증발이 쉽게 일어나게 되고 또한 난류효과를 증대시키는 요인이 되기 때문이다. 따라서 냉각재상실사고의 진행과정에서 첨두피복관온도가 발생하는 재관수 구간의 수면 위쪽에서 유지되는 DFFB에서의 정확한 열전달을 계산하기 위해서는 이들의 고려가 필요하다. 본 논문에서는 DFFB에서 지지격자의 존재로 인해 물방울이 잘게 부수어져 증발이 쉽게 이루어지도록 하는 Droplet Breakup Model을 냉각재상실사고 최적해석 코드인 RELAP5/MOD2에 삽입하였다. 재관수 구간에서 지지격자의 영향을 체계적으로 조사한 FEBA 실험에 대해서 검증계산을 수행하여 실험자료와 비교하였다.

I. Introduction

Recent experiments [1,2,3] show that the existence of spacer grid improves the heat transfer. Since the grid reduces the fuel assembly flow area, the flow contracts and then expands downstream of each grid. The local heat transfer within and downstream of the grid is increased due to the disruption and the reestablishment of the fluid and thermal boundary layers. The enhancement of the continuous phase heat transfer downstream of a spacer grid can be explained by an entrance effect and it decays exponentially downstream of the grid [4,5].

When the flow is a dispersed two-phase droplet flow which prevails in low flooding rate PWR reflood, the grids promote additional heat transfer effects. Since there is no heat generated in the grid, they can quench before the fuel rods. If the grids quench, they increase the effective interfacial area, which can lower the vapor superheat in the nonequilibrium two-phase droplet flow. A wetted grid will have a higher interfacial heat transfer coefficient than the droplets, since the relative velocity of the vapor flow to the liquid film is larger. In addition to desuperheating the vapor, the liquid film will evaporate, resulting in higher convective heat transfer due to higher steam flow. The increased interfacial heat transfer between the grid and the vapor and the generation of additional saturated vapor from the liquid film on the grid will result in lower vapor temperatures downstream of grids. In addition to grid rewetting, the grids can also cause shattering of the entrained droplets into smaller ones which can be more easily evaporated. The evaporation of the smaller shattered droplets provides an additional steam source, which also increases the convective heat transfer rate.

Exact calculation of heat transfer in the dispersed flow film boiling(DFFB) regime is very important during the reflooding phase of a loss of coolant accident(LOCA) because the long duration of this heat transfer regime occurs in the upper side of fuel rod at which peak cladding temperature (PCT) happen. In this paper, therefore, droplet breakup model at spacer grid has been developed and incorporated into RELAP5/MOD2 [6]. The method in the present paper is mainly based on the previous work [2]. Verification calculations are performed for FEBA test 216 and 223 [7].

II. Droplet Breakup Model

Droplet breakup model calculates the enhanced vapor generation rate resulting from the rapid evaporation of small drops generated by shattering at spacer grids under the following restrictions.

- It is not implicitly coupled with the hydrodynamic solution.
- Quasi-steady state is assumed.
- It is not operable for negative flow.

II.1 Droplet Breakup

The mass source of shattered drops generated by droplet breakup at spacer grid is calculated from

$$\dot{m}_{SD} = \eta\left(\frac{A_G}{A_C}\right)\dot{m}_e \qquad (1)$$

Where η is grid efficiency factor (the portion of drop within the grid projected area that is shattered into small drops).

Sauter mean diameter of the small drops is [2]

$$\frac{D_{SD}}{D_I} = 6.167\ We_D^{-0.53} \qquad (2)$$

If the impact droplet weber number, We_D, is less than 80, droplet breakup is neglected [8]. The number flux for small drops can be calculated from the above two equations.

$$N_{SD} = \frac{6\ \dot{m}_{SD}}{\pi\ \rho_\ell\ D_{SD}^3} \qquad (3)$$

II. 2 Droplet Evaporation

Vapor generation rate from a single drop is

$$\Gamma = h_i \cdot \pi D^2_{SD}\left(\frac{T_g - T_s}{h_{fg}}\right) \tag{4}$$

The interfacial heat transfer coefficient including the effect of vapor leaving the drop surface is given by [9]

$$h_i = \frac{k_g(2+0.55\, Re_{SD}^{1/2}\, Pr_g^{1/3})}{D_{SD}\,\{1+0.5\, C_{pg}(T_g - T_s)/h_{fg}\}} \tag{5}$$

Equation (4) can be represented as follows by introducting

$$\Gamma = C_\Gamma \cdot D_{SD} \tag{6}$$

where

$$C_\Gamma = \frac{k_g(2+0.55\, Re_{SD}^{1/2}\, Pr_g^{1/3})\, \pi\, (T_g - T_s)}{h_{fg} + 0.5(h_g - h_{gs})} \tag{7}$$

Under the assumption C_Γ and V_{SD} are constant, the exit drop diameter is given from the mass conservation

$$D_{SD,\,2} = \left[D_{SD,1}^{2} - \frac{4 C_\Gamma}{\pi\, \rho_\ell\, V_{SD}} \Delta z\right]^{1/2} \tag{8}$$

Then, the vapor generation rate in a volume (i) is

$$\Gamma_i = N_{SD} \cdot \frac{\pi}{6}(D_{SD,\,1}^{3} - D_{SD,\,2}^{3})\, \rho_\ell \tag{9}$$

Drop exit velocity is calculated approximately from a simplified momentum equation

$$V_{SD,\,2} = \left[V_{SD,\,1}^{\,2} + 2\left\{\frac{3\, C_D \rho_g (V_g - V_{SD,\,1})^2}{4\, \rho_\ell\, D_{SD,\,1}}\right\} \Delta z\right]^{1/2} \tag{10}$$

with drag coefficient, C_D[2,6]

$$C_D = \frac{24}{Re_{SD}}(1 + 0.1\, Re_{SD}^{0.75}) \tag{11}$$

The exit drop diameter and velocity are used to calcuate the evaporation constant, C_Γ, for the next node, and so forth. This process continues until all small drops are completely evaporated or next spacer grid is encountered.

II. 3 Incorporation into RELAP5/MOD2

The above mentioned droplet breakup model is incorporated into the RELAP5/MOD2 cycle 36.05. Grid flag is given for the volume which includes the spacer grid. This model is applied for the post dryout dispersed flow regime only under the assumption that the spacer grid is located at the bottom of considered volume. The droplet portion which is broken up into small drops is excluded for the calculation of volumetric interfacial heat transfer coefficient in the original RELAP5. *But the amout of evaporation from the* shattered small drops are calculated using the above model and then converged into the equivalent volumetric interfacial heat transfer coefficient

$$H^*_{ig} = \frac{(h_{gs} - h_f)\, \Gamma_i}{T_g - T_s} \tag{12}$$

This is added to the volumetric interfacial heat transfer coefficient calculated from the original RELAP5 excluding the droplet portion which is broken up. The flow chart is shown in figure 1.

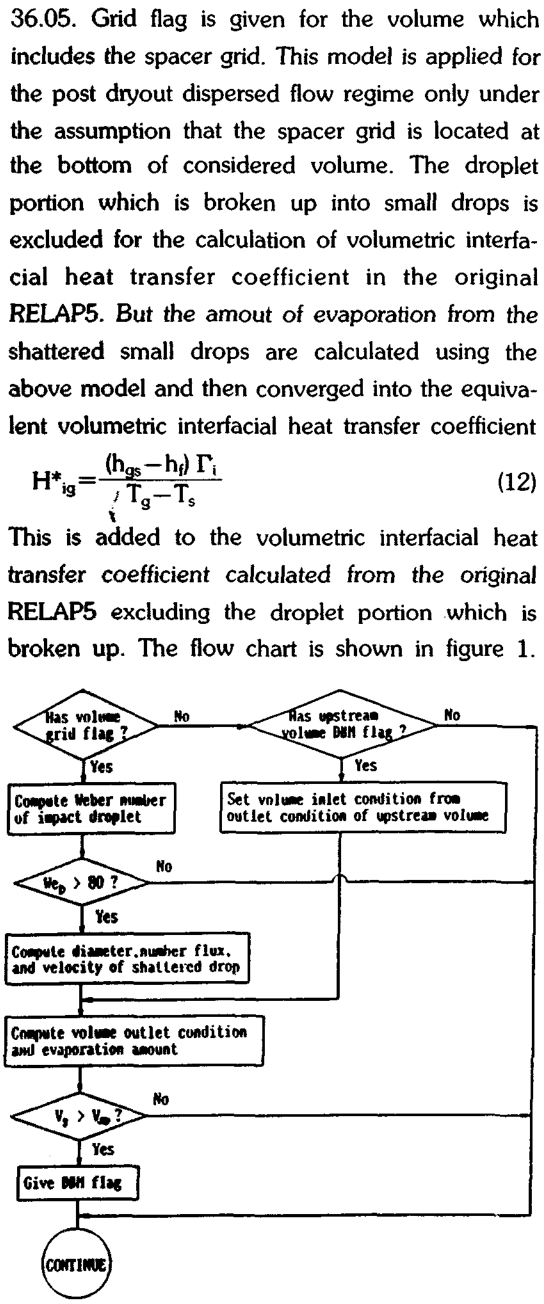

Fig. 1 Flow Chart of Droplet Breakup Model

III. Verification Calculation for Feba Tests

III. 1 Brief Description of FEBA Tests [1,7,10]

The FEBA (Flooding Experiments with Blocked Arrays) tests were the first reflooding experiments to systematically examine the thermalhydraulic performance of grid spacer during reflood, The tests used a 5×5 electrically heated rod bundle with a flat chopped cosine power shape and a heated length of 3.9m (figure 2).

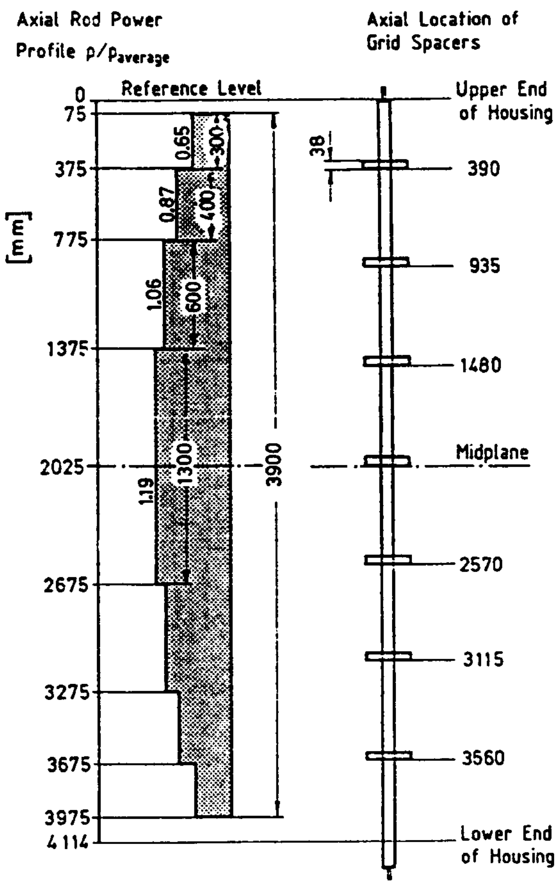

Fig. 2 Heater Rod and Axial Power Profile of FEBA [1]

The tests were conducted from series I to series VIII to show the separate effects of grid spacer and blockage on reflood heat transfer. System pressures and flooding velocities of 2 throught 6 bar and 2.2 through 5.8 cm/s, repectively, were applied for most of the test series. Typical transients measured and evaluated from the different test series were cladding and fluid temperatures, heat transfer coefficients, pressure differences and water carry over.

The early portion of the reflood phase is characterized by mist flow regime for almost part axially. Water droplets are entrained by highly superheated steam. Flow obstacles such as grid spacers and blockage increases local turbulance as well as droplet evaporation leading to significant increase of local heat transfer. This effect compensates to a

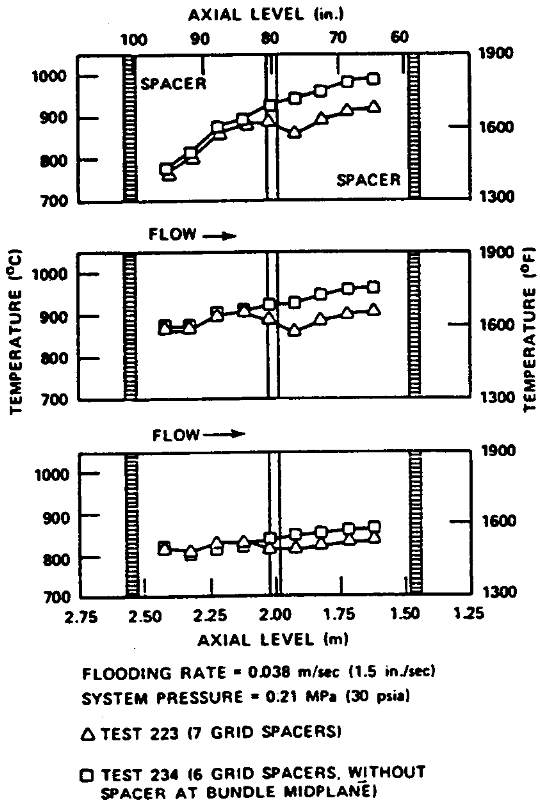

Fig. 3 Influence of Grid Spacer on Axial Cladding Temperature Transient with and without Grid, FEBA [1,2]

large extent local coolant mass flux reduction due to blockages with bypass.

Several experiments were performed under similar conditions with and without the midplane grid spacer in place. As shown in figure 3, the presence of the midplane grid spacer results in improved cooling due to the heat transfer effects of convective enhancement, grid rewetting, and droplet breakup. Both FEBA test 223 and test 234 had 2.1 bar pressure and 3.8 cm/s constant flooding velocity.

III.2 Relap5/MOD2 Modelling

FEBA test 216 and 223 are chosen as reference experiments for comparison and verification of droplet breakup model at grid spacer. Experimental conditions are compared in table 1. Two tests have similar experimental parameters except the system pressure. Therefore, the pressure sensitivity of RELAP5/MOD2 prediction capability for reflood can be shown.

Figure 4 shows the RELAP5 nodalization for FEBA test facility. Heated part is modelled by the pipe component with 20 subvolumes divided based on the power profile. Central region (high power) is divided in detail whereas top and bottom regions (low power) are divided roughly.

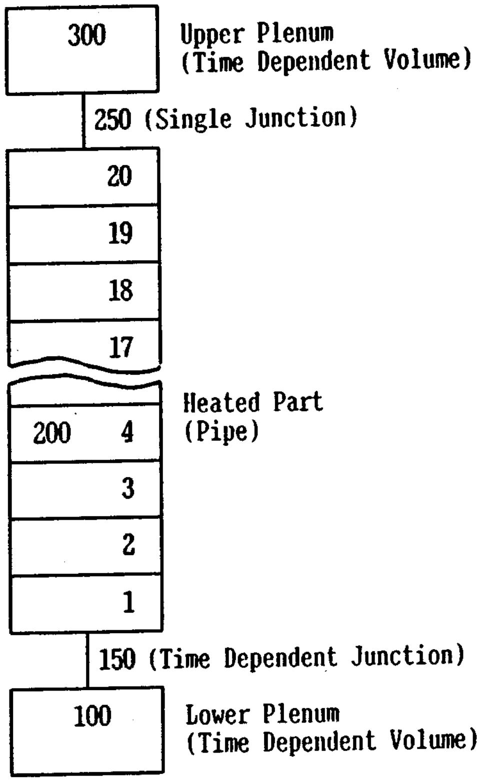

Fig. 4 RELAP5 Nodalization for FEBA Test Facility

Flooding velocity is given by the time dependent junction and system pressure is controlled by the time dependent upper plenum pressure. Fuel rod

Table 1. Experimental Conditions of FEBA Test No. 216 and 223

Test Parameters	Test No. 216	Test No. 223
Flooding velocity (cm/s)	3.8	3.8
System pressure (bar)	4.1	2.2
Feedwater temperature (℃)		
start	48	44
end	37	36
Initial midplane cladding temperature (℃)	787	763
Initial midplane housing temperature (℃)	640	671

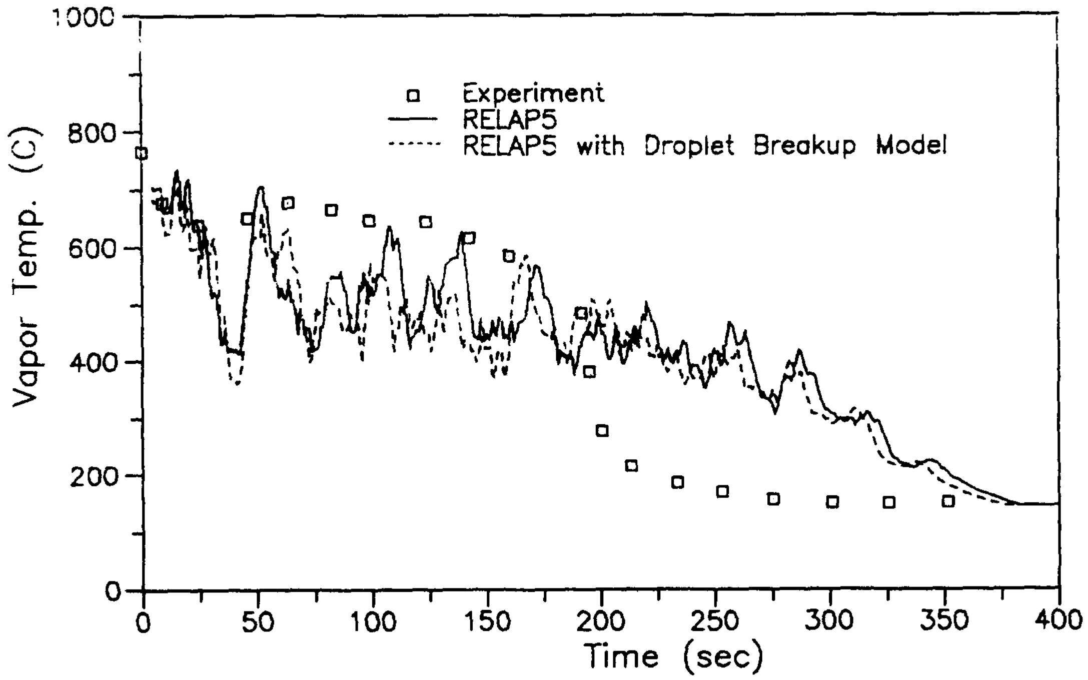

Fig. 5 Vapor Temperatures at Volume 12 (FEBA 216)

simulator is divided into seven intervals (eight mesh points) radially and reflood fine mesh rezoning option is used. One channel core modelling is enough because all rods have same axial power profile.

III. 3 Calculation Results and Discussion

RELAP5 calculation with and without droplet breakup model at grid spacer are performed for FEBA test 216 and 223. Figure 5 shows the vapor temperatures of volume 12. Experimental data fall to near saturation temperature about 200 seconds but still have temperature jump occasionally until quenching time. This means that, even though the actual vapor is in superheated state the saturation temperature is measured because the sensor of thermocounle is wetted by entrained droplets prior to the quenching of rod surface. Vapor temperatures plotted directly from RELAP5 have great oscillation and the comparison between two outputs is impossible. Therfore, they are averaged every ten seconds. Vapor temperature is lowered when the droplet breakup model is used as expected. Volume 12 locates between the spacer grids. If the volume which indlude spacer grid is compared, the vapor temperature difference will be large considerably.

Figure 6 shows the cladding surface temperature at volume 12. RELAP5 predicts fairly well except the quenching time. Quenching is delayed due to the severe criterion of RELAP5. Enhanced heat transfer due to droplet breakup model at spacer grid reduces the cladding temperature compared to the case without the model.

Figure 7 shows the integrated water carry-over at core exit (RELAP5) and at water collecting tank (experiment). Large difference between RELAP5 and experiment is caused mainly by the overprediction of RELAP5 and partly by the different

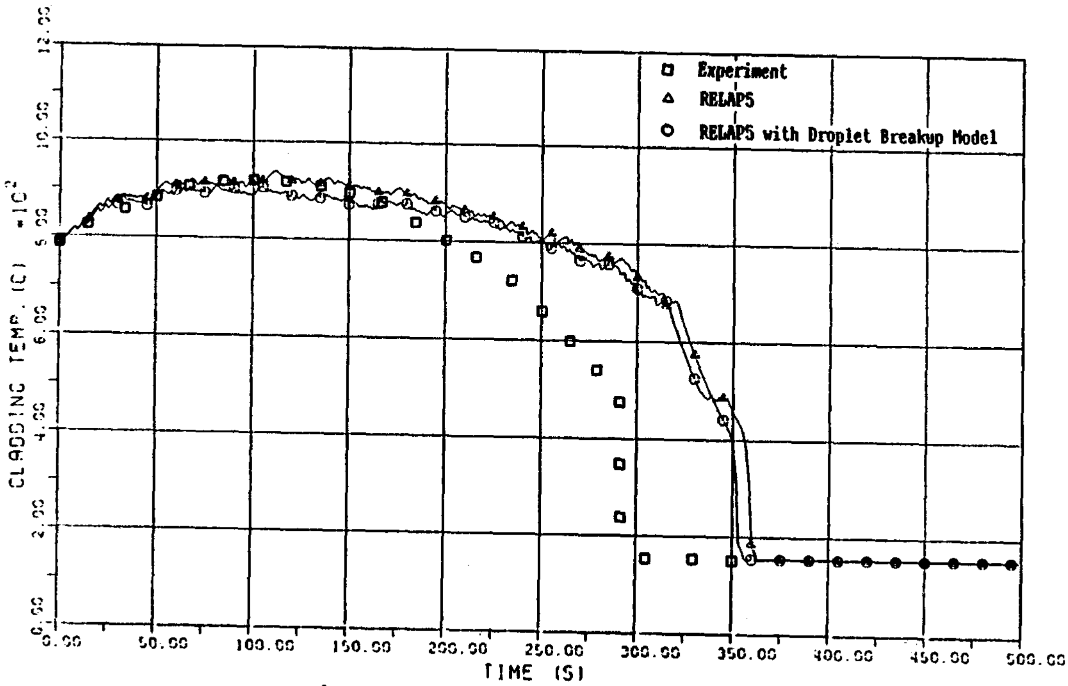

Fig. 6 Cladding Surface Temperature at Volume 12 (FEBA 216)

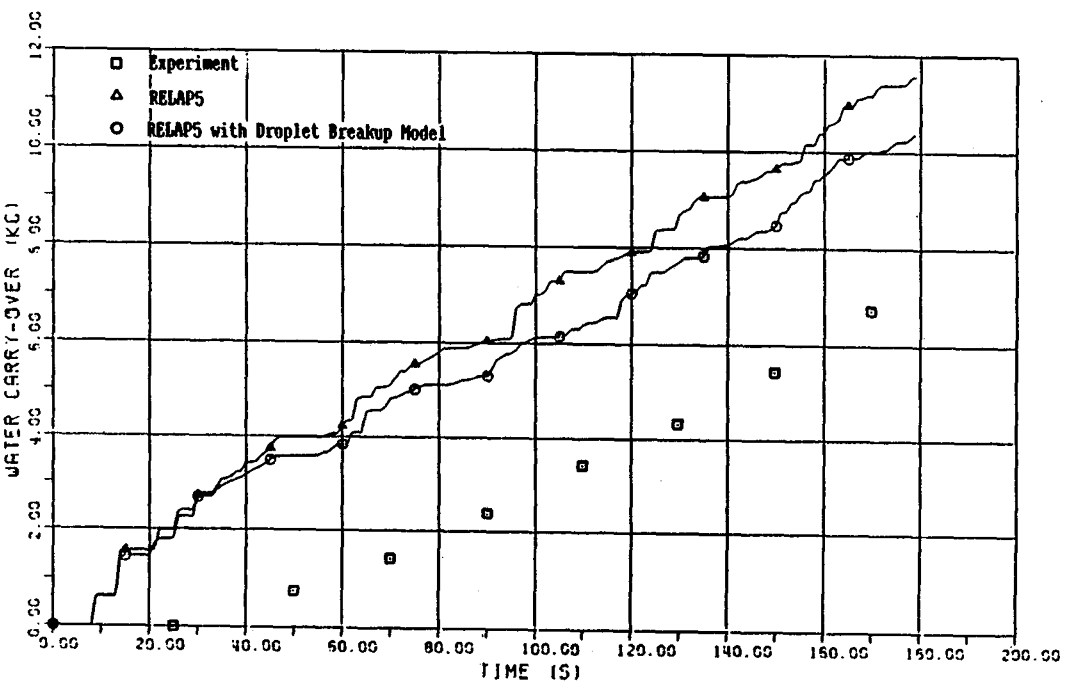

Fig. 7 Integrated Water Carry Over (FEBA 216)

locations of comparison point. Delay time which water flow through the pipe from the core exit to the water collecting tank is not considered in RELAP5. Entrainment is overpredicted especially in early period of reflood. It is originated from the relatively large volume size of the lowest volume in which inverted slug and slug flow regime is maintained. It is shown that the application of the droplet breakup model reduces the droplet entrainment by the enhanced vaporization and gets near to the experimental data.

Figure 8 and 9 show the cladding surface temperatures at two different locations for FEBA test 223. RELAP5 overpredicts the cladding temperature compared to the case of FEBA test 216. The overprediction in the lower level comes from the slow growth of water level due to the excessive entrainment in the early period of reflood.

Figure 10 shows the axial distribution of cladding surface temperatures with and without droplet breakup model at midplane spacer grid. Droplet breakup model increases the heat removal, therefore, reduces the peak cladding temperature in accordance with the experimental data of figure 3. Absolute temperature difference between two cases predicted from RELAP5 is small compared to that of experiment. This can be expected because only droplet breakup model is considered. If the effect of grid rewet and turbulance is considered, the temperature difference will be increased and get closer to the experimental data.

IV. Conclusion

• Droplet breakup model enhances the vapor generation, therfore, reduces the vapor and cladding temperature comparéd to the case without the model.

• Some deficiencies of RELAP5/MOD2 are

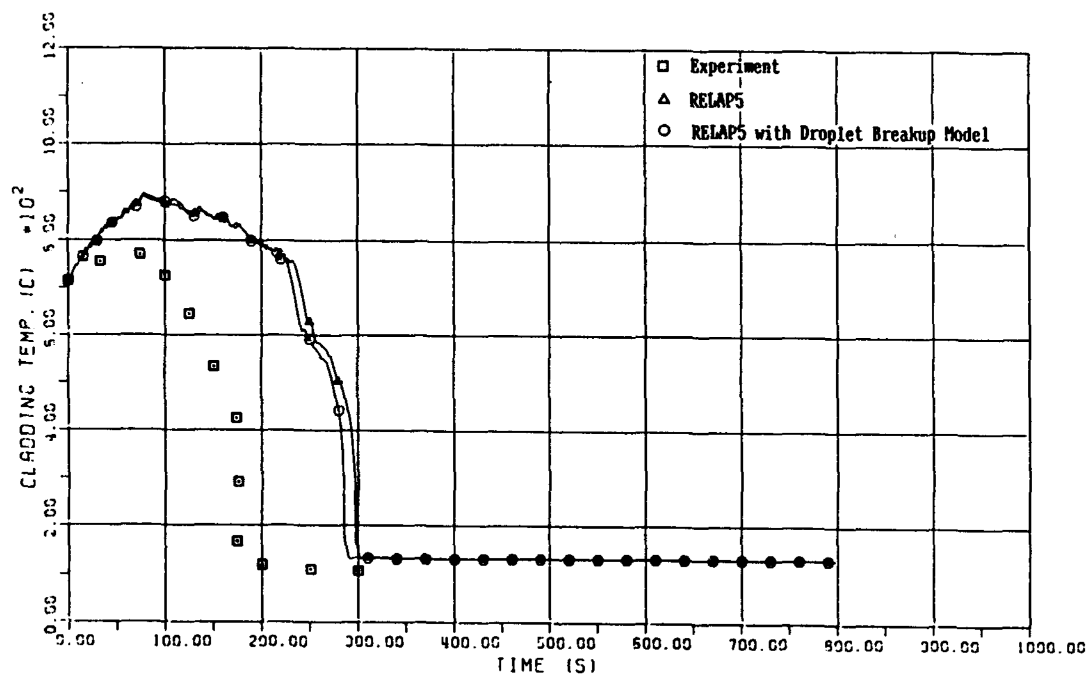

Fig. 8 Cladding Surface Temperature at Volume 6 (FEBA 223)

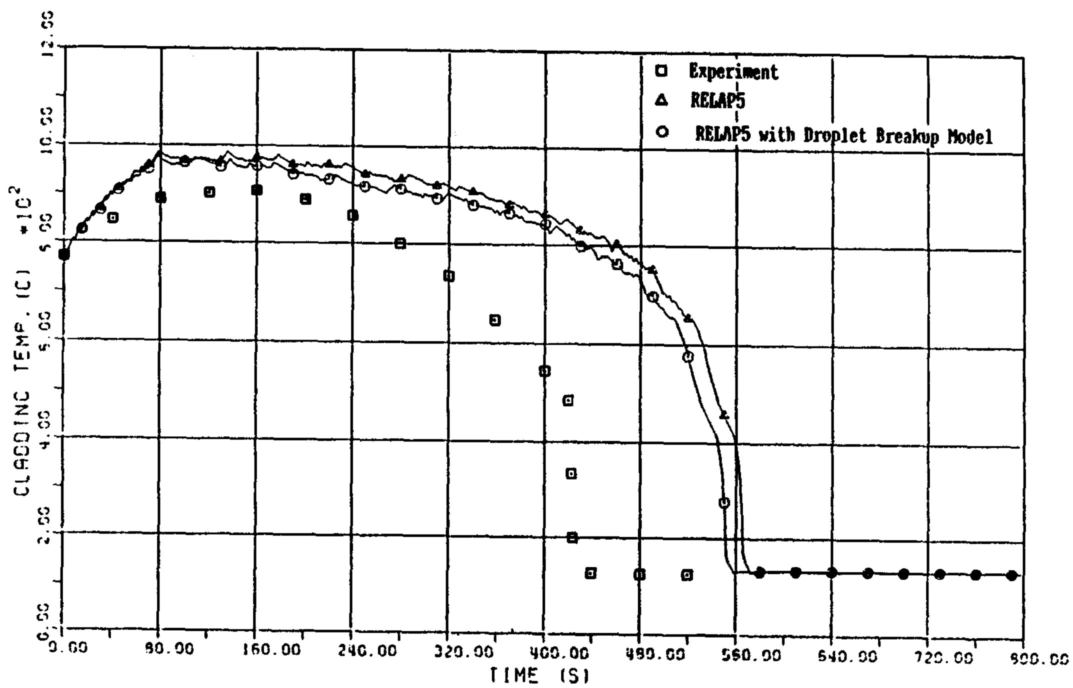

Fig. 9 Cladding Surface Temperature at Volume 12 (FEBA 223)

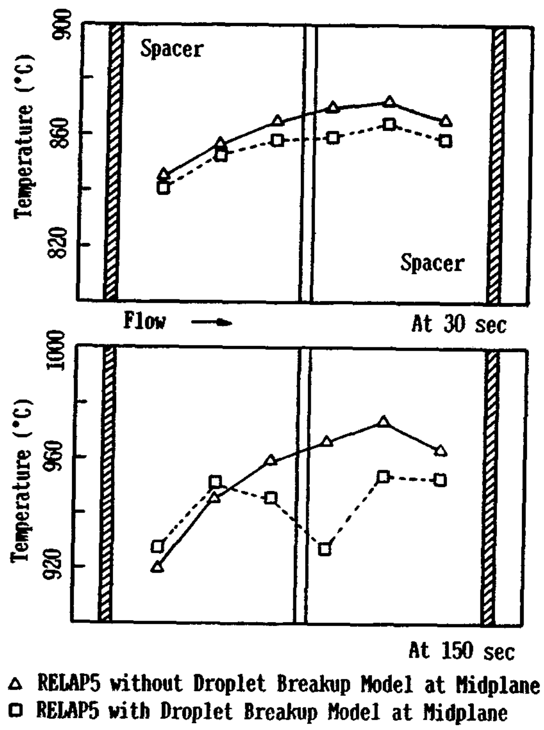

Fig. 10 Axial Cladding Temperature Transient from RELAP5 with and without Droplet Breakup Model at Midplane Spacer Grid (FEBA 223)

found. They are underprediction of vapor and cladding temperatures especially in high pressure reflooding, overprediction of liquid entrainment, and delay of quenching time due to severe criterion of quenching conditions.

• The other phenomena such as grid rewet and turbulence enhancement should be considered to get better results.

Nomenclature

A_c	Cross-sectional area of flow channel
A_G	Grid spacer projected area
C_D	Drag coefficient
C_Γ	Evaporation constant defined in Fq.(7)
C_P	Specific heat
D	Droplet diameter
h	Specific enthalpy
h_{fg}	Latent heat of vaporization
h_i	Interfacial heat transfer coefficient
H^*_{ig}	Equivalent volumetric interfacial heat transfer coefficient defined in Eq.(12)
k	Thermal conductivity
$\dot{m}_e$	Droplet mass flow rate before dreakup
$\dot{m}_{SD}$	Mass flow rate of shattered drops by droplet breakup
N_{SD}	Small drop number flux (number of drops per second)
Pr	Prandtl number
Re_{SD}	Drop Reynold number $=\frac{\rho_g(V_g-V_{SD})D_{SD}}{\mu_g}$
T	Temperature
V	Velocity
V_{DI}	Velocity of impacting drop normal to surface
We_D	Droplet impact Weber number $=\frac{\rho_g V^2_{DI} D_I}{\sigma}$
Δz	volume height
ρ	Density
η	Grid efficiency factor
σ	Surface tension
Γ	Vapor generation rate from one drop
μ	Dynamic viscosity
	Subscript
1	volume inlet
2	volume exit
g	superheated vapor
I	impact
l	liquid
s	saturation
SD	Small drop

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