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Analysis of Fuel/Coolant Mixing in Steam Explosion

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증기 폭발시 용융 핵연료/냉각수 혼합에 대한 해석

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Abstract

A required initial condition for a steam explosion to occur following core meltdown accidents of a nuclear power plant is the formation of a coarse mixture of molten fuel and water. The extent of a premixing is the measure of efficiency of steam explosion that may follow. A simple one-dimensional, transient model and the flooding criteria have been applied to evaluate the fuel/coolant mixing limit. Also, both instant breakup and dynamic breakup models for the mixing process have been separately used here and compared each other. The results indicate that fuel temperature, ambient pressure, mixing diameter, water depth, and pouring diameter are the important parameters affecting the mixing behavior.

요 약

중대 사고에 이어 형성 될 수 있는 용융 핵연료와 냉각수의 혼합체는 그 후에 일어날 수 있는 증기 폭발의 초기 조건을 이루게 되며, 또한 이러한 혼합의 정도는 증기 폭발의 강도를 결정하는 주요 요인이 된다. 본 연구는 간단한 일차원 과도 상태 모형을 이용하여 용융 핵연료와 냉각수의 혼합의 한계를 결정하였으며, 용융 핵연료의 분쇄 과정을 모사 하기 위하여 동적 분쇄모형과 순간 파열 모형을 각각 적용하여 그 결과를 비교하였다. 계산 결과에서는 용융 핵연료의 온도, 압력, 수조의 깊이, 혼합 상태에서의 분쇄물 직경 그리고 용융 핵연료 입사 직경등이 혼합량에 영향을 미치는 주요한 인자들로 나타났다.

1. Introduction

During a severe accident in a nuclear power plant when the reactor core melts, the contact of the molten core material with water can lead to violent interactions such as steam explosion. If these fuel/coolant interactions(FCI) occurr, the integrity of the pressure vessel and containment may be threatened. The intensity of steam explosion is dependent on the degree of the fuel/coolant mixing amount, which is determined at the premixing stage before the explosion. This mixing stage is characterized by two phenomena : transfers heat from hot fuel to the coolant in film

boiling mode and the fuel breakup into smaller particles, and thus sets up initial conditions for a possible steam explosion that may follow. Many models for simulating the mixing phenomena have been developed, but it is difficult to evaluate correct mixing amount and define the mixing state. Most of previous works on mixing concerned to the phenomenological understanding about the transient fluid motion, heat transfer between fuel and coolant, and physical limits on mixing. Recently, Corradini [1] and Corradini and Moses [2] have proposed a simplified transient model which allows for the radial expansion of mixed fuel particles as they fall through the water pool and are fragmented. The fuel particle diameter and volume were taken to be empirical functions of dimensionless time obtained from the FIT's experiments [3]. Chu et al. [4] developed a complete set of constitutive relations for interfacial mass, momentum and energy transport. The key constitutive relation is obtained from the fuel fragmentation model based on Rayleigh–Taylor instabilities, which cause the fuel to be dynamically fragmented from its initial entry diameter to smaller sizes. This mixing model has incorporated all the insights of previous analyses, but is still limited by a one–dimensional treatment because the real mechanism of the mixing process includes the multi–dimensional effects.

In this study, the amount of molten fuel premixed with the coolant water is estimated using a one–dimensional transient model with the fluidization limit criteria. Dynamic break–up model which considers the Rayleigh–Taylor instability is applied to the model simulating mixing process. The model is compared for the cases of the instant breakup condition and continuous breakup condition. Finally, the sensitivity study has been performed for the parameters which influence the fuel/coolant mixing limit. Additionally, in order to visualize the mixing process, a graphic presentation module has been developed.

2. Modeling

In this study, the fluidization criteria is selected as a mixing limit condition, which can be calculated from the drift–flux model and the flooding criteria.

In the drift–flux model, an average velocity of vapor, V_g, is expressed as,

$$V_g = C_0 j + V_{gj} \tag{1}$$

For churn–turbulent flow, the drift velocity is given by terminal rise velocity, U_t, as following,

$$V_{gj} = U_t = 1.53\left[\frac{\sigma g(\rho_f - \rho_g)}{\rho_f^2}\right]^{3/4} \tag{2}$$

where σ : bubble surface tension
ρ_f : liquid density
ρ_g : vapor density

Since the liquid superficial velocity is zero at the flooding point, the vapor velocity, V_g, can be set to j_g/α. Thus, we obtained following expression from Eqs. (1) and (2);

$$\left(\frac{1}{\alpha - C_0}\right) j_g = 1.53\left[\frac{\sigma g(\rho_f - \rho_f)}{\rho_f}\right]^{1/4} \tag{3}$$

Applying the flooding condition criterion by Wallis [5], the flooding void fraction, α_v, is given by

$$\alpha_v \frac{1}{C_0 + a} \tag{4}$$

where

$$a = 1.7\left[\frac{\sigma \rho_g^2}{\rho_f g D_H (\rho_f - \rho_g)}\right]^{1/4} \tag{5}$$

where D_H is the variable hydraulic diameter of the pool to treat the shadowing effect on flow area by increase of the fuel population. The expression for D_H is as follows;

$$D_H = \frac{4\{A_{ch} - N\pi(D_{mix}/2)^2\}}{P_H + N\pi D_{mix}} \tag{6}$$

where A_{ch} and N are pool area and number of fuel particles, respectively.

As a fuel jet falls into the water pool, it begins

to be distorted in shape due to Kelvin–Helmholtz instabilities and Rayleigh–Taylor instabilities, and is mixed with water in film boiling. The fuel continues to break apart into smaller particles with the surrounding water. If the characteristic Weber number exceeds a critical value($We_{crit}=12$), the breakup occurs. From the above assumptions and theoretical correlations, the breakup diameter, D_f, can be calculated from initial diameter, D_{fo},as following[4],

$$D_f=D_{fo}\exp(-C_1(T^+)^{C_2}We^{C_3}) \quad (7)$$
$$C_1=0.1708-0.149(\rho_c/\rho_f)^{0.5}$$

where C_2 and C_3 are empirical constants equal to 0.772 and 0.246, respectively. Dimensionless time T^+ is defined by

$$T^+=\frac{V_f t}{D_{fo}}\left(\frac{\rho_c}{\rho_f}\right)^{1/2} \quad (8)$$

But the prediction of fuel fragmetation using this model is dependent on the history of the droplet and its surrounding hydrodynamic conditions. This can cause difficulties when the flow parameters around the droplet change rapidly with time or space. Thus, Chu[4] proposed that a time-indenpendent model is adequate to predict the transient droplet size when the local density ratio and local relative velocity effects can not be neglected. The droplet size at a new time step [n+1] can be predicted by the variables at the old time [n], as following ;

$$D^{n+1}=D^n(1-C^*\Delta T^+We^{C_3}) \quad (9)$$

where C^* is an empirical constant equal to $0.1093-0.078(\rho_c/\rho_f)^{0.5}$.

To calculate the fuel falling velocity and void fraction, the following simplifying assumptions are used :

(1) The flow is one-dimensional.
(2) Water and steam are assumed to be at the saturation temperature.
(3) Liquid and vapor are incompressible.

Based on the above assumptions, the void fraction is calculated by the void propagation equation given by

$$\frac{\partial\langle\alpha\rangle}{\partial t}+C_k(\langle\alpha\rangle)\frac{\partial\langle\alpha\rangle}{\partial z}=\Omega(\langle\alpha\rangle) \quad (10)$$

where the characteristic reaction frequency, Ω, is given by

$$\Omega=\left[1-C_o\langle\alpha\rangle\frac{(\rho_c-\rho_g)}{\rho_c}\right]\frac{\langle\Gamma_g\rangle}{\rho_g}$$

and Γ_g is the vapor source term expressed as follows ;

$$\langle\Gamma_g\rangle=\frac{P_H\, q''}{A_{x-s}h_{fg}}$$

The velocity of the kinematic wave, C_k, is given by

$$C_k=C_o\langle j\rangle+V_{gj}$$

where V_{gj} is the void fraction averaged drift velocity and 1.14 is used as C_o in this study.

The fuel falling velocity and position are calculated by following momentum balance equation which considers drag forces ;

$$m_f\frac{dV_f}{dt}=-m_fg+\frac{\rho_c g\, m_f}{\rho_f}+\frac{1}{2}C_D(\alpha_f)A_fV_f^2 \quad (11)$$

where mf is fuel particle mass, A_f is the total particle surface area and the drag coefficient is given as,

$$C_D=0.45\left[\frac{1+17.67(1-\alpha_f)^{9/7}}{18.67(1-\alpha_f)^{1.5}}\right]^2 \quad (12)$$

In the interface between fuel particles and water, two modes of heat transfer exist, i. e., radiation and conduction across the vapor film. The heat flux to water is considered to be the linear summation of radiation and conduction across the vapor film as,

$$q=(h_{rad}+h_{film})(T_p-T_{sat}) \quad (13)$$

where T_p is droplet temperature.

The radiation heat transfer coefficient, h_{rad}, is given by gray body formulation

$$h_{rad}=\frac{\sigma E_p(T_p^4-T_{sat}^4)}{T_p-T_{sat}} \quad (14)$$

where σ is the Stefan–Boltzmann constant and E_p is the fuel particle emissivity.

The conduction heat transfer coefficient h_{film} is given by

$$h_{film}=0.425\left[\frac{h'_{fg}(\rho_c-\rho_g)k_g^3\rho_g g}{D_p\mu_g(T_p-T_{sat})}\right]^{1/4} \quad (15)$$

where

$$h'_{fg}=h_{fg}+0.68C_{pg}(T_p-T_{sat})$$

3. Results of Sensitivity Study

The parameter ranges used for sensitivity study in this study are ;

○ water depth : 1 m −3 m

○ fuel temperature : 2500 K–3200 K

○ ambient pressure : 0.1MPa–1.5MPa

Fig.1 shows the void fraction growth as functions of time and elevation from the chamber base. The fluidization occurs when the void fraction exceeds about 0.8. Thus, it is found that the available time for mixing is less than 0.5sec. Fig.2 shows the dependency of mixing amount on pressure effect. Since the increase in ambient pressure decreases the void fraction generation rate, more fuel could be mixed before fluidization. Fig.3 shows the effect of temperature. As the fuel temperature decreases, both fuel heat flux and vapor generation rate decrease. Therefore, more amount of fuel mass could mix with coolant before fluidization, also. Fig.4 shows the negligible

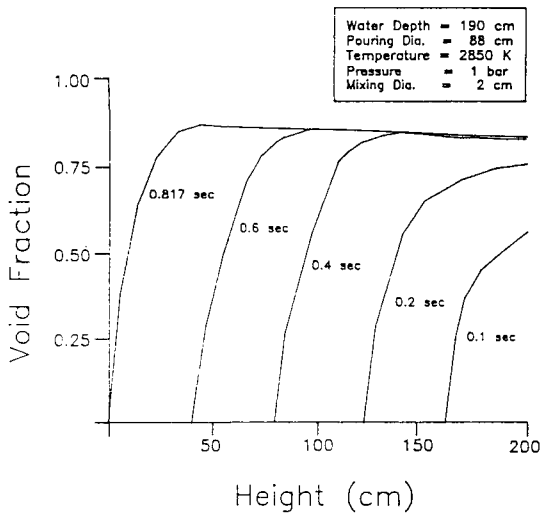

Fig. 1. Void Fraction Growth in Instant Breakup Model

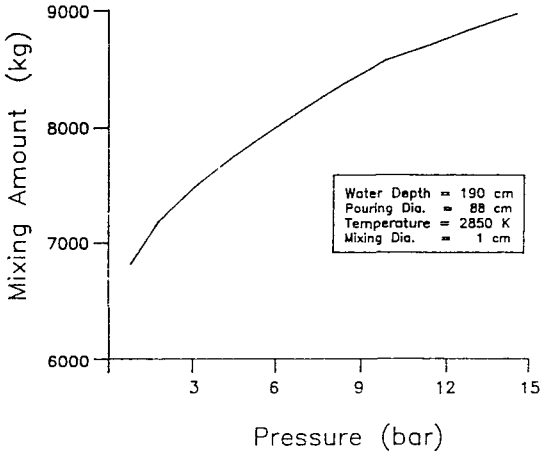

Fig. 2. Amount of Mixing as a Function of Ambient Pressure in Instant Breakup Model

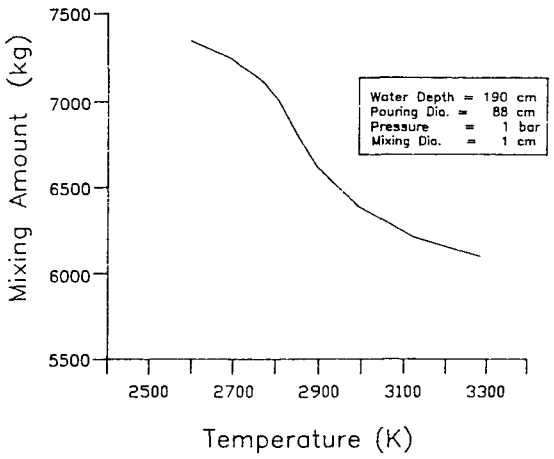

Fig. 3. Amount of Mixing as a Function of Fuel Temperature in Instant Breakup Model

effect of water depth on the mixing amount.

In the dynamic breakup model, the final fuel size distribution is obtained in the range of 1–4 mm diameter. Since the fuel breakup mechanism is extremely short-time phenomena, this fuel size reduction rapidly increases the heat transfer area. This limits the amount of mixed fuel with water. Figs. 5, 6, 7, and 8 show the results of sensitivity study by the dynamic breakup model. The dependency of mixing amount on temperature and pressure is similar to the instant breakup model. However, the mixed amount is incresed with pool depth to a certain distance. In the case of pouring diameter of 44cm, inlet velocity of 590cm/sec, pressure of 1 bar and fuel temperature of 2850 K, the mixing amount is saturated to~1000kg for~170cm of water depth.

The graphic module obtains the data from the calculation module and displays void fraction growth and fuel column/particle motion at each time step. The example graphic displays for mixing process are shown in Figs. 9, 10, 11 and 12.

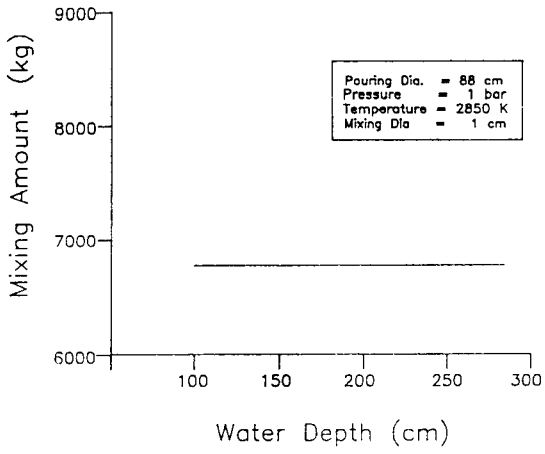

Fig. 4. Amount of Mixing as a Function of Water Depth in Instant Breakup Model

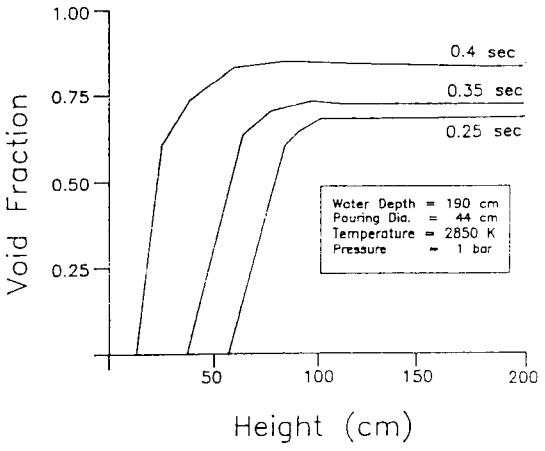

Fig. 5. Void Fraction Growth in Dynamic Breakup Model

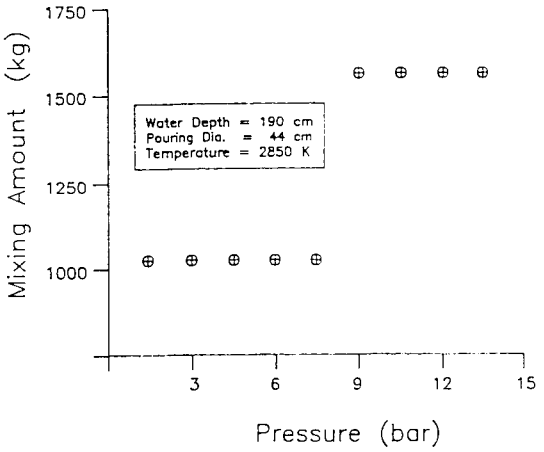

Fig. 6. Amount of Mixing as a Function of Ambient Pressure in Dynamic Breakup Model

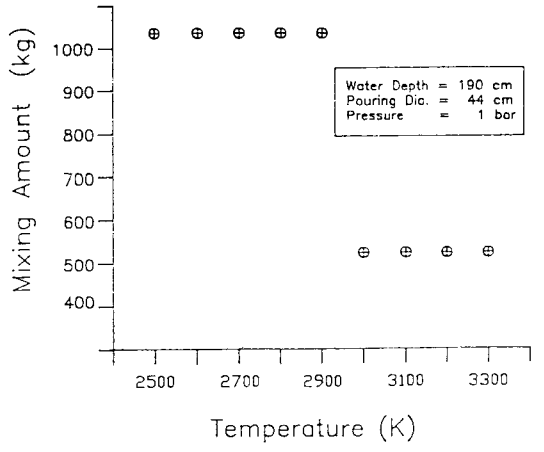

Fig. 7. Amount of Mixing as a Function of Fuel Temperature in Dynamic Breakup Model

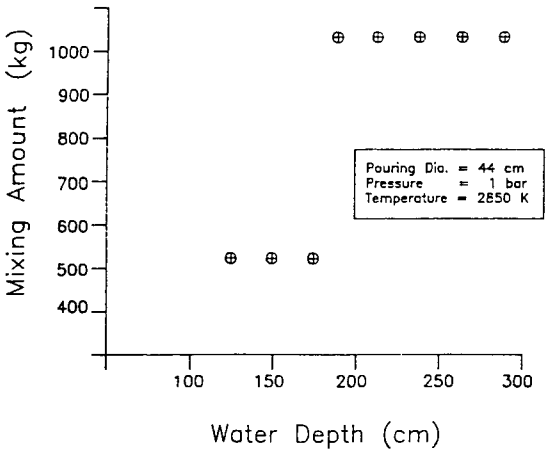

Fig. 8. Amount of Mixing as a Function of Water Depth in Dynamic Breakup Model

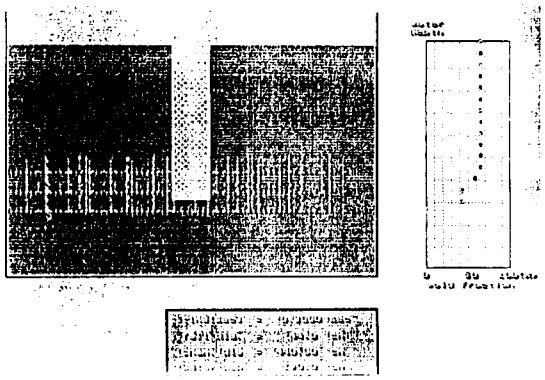

Fig. 9. Graphic Representation of Mixing Process : 1

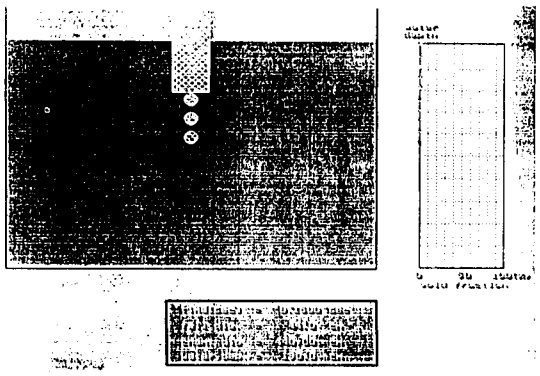

Fig. 10. Graphic Representation of Mixing Process : 2

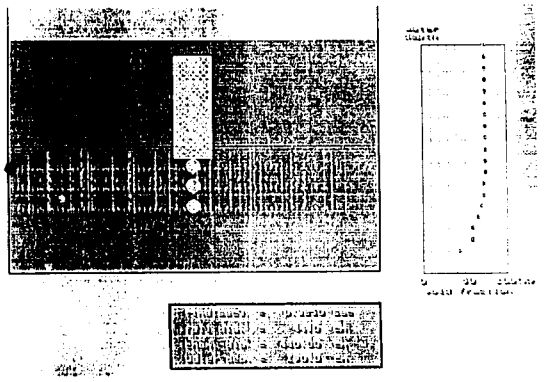

Fig. 11. Graphic Representation of Mixing Process : 3

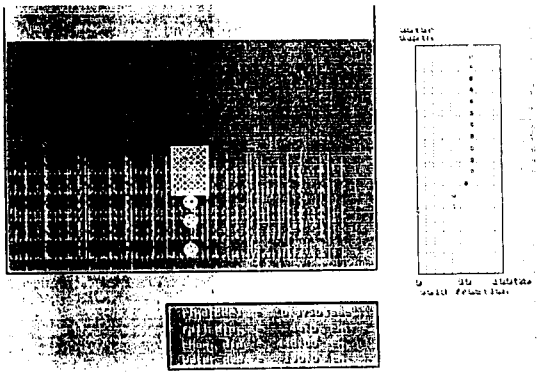

Fig. 12. Graphic Representation of Mixing Process : 4

4. Discussion and Conclusions

In this study, the amount of fuel/coolant mixing is estimated using a simple one-dimensional transient model. As a limiting condition for mixing, the fluidization criterion has been adopted, which can be obtained from the drift-flux model and flooding criteria. A transient calculation of the axial void fraction and falling velocity is performed using the momentum and heat transfer balance equations. To simulate the mixing phenomena, the dynamic breakup model which considers Rayleigh-Taylor instability is used. From the calculation results, it is

concluded that the increases in water depth and pressure enhance the premixing. However, as the fuel temperature increases the limit decreases due to more rapid generation of void.

The results show that the instant breakup model is more conservative than the dynamic breakup model, and the dynamic break up model can be regarded as the realistic process. But the model problems is remained, such as breakup time setting, and decision of partcle positions after break up. Therefore, the improvement of breakup mechanism is highly recommanded, and also two--dimensional approach and experiments for benchmark are needed.

Nomenclature

A	cross sectional area
C_D	drag coefficient
C_o	*void distribution parameter*
C_p	specific heat
D_H	hydraulic diameter
D_{mix}	mixing diameter
g	gravitaional acceleration
h	heat transfer coefficient
h_{fg}	latent heat of vaporization
j	superficial velocity
k	thermal conductivity
m	mass
P_H	heated perimeter
q	heat flux
t	time
V	velocity
V_{gj}	drift velocity
α	void fraction
ρ	density
σ	surface tension

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