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A Debris Bed Model with Gas Inflow and Gas Upflow for Debris/Water/Concrete Interaction and Its Application under Severe Accident Condition in LWR.

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개스 Inflow와 Upflow를 갖는 Debris/Water/Concrete상호작용 해석용 Debris Bed 모델 및 중대사고 조건에 그 적용해석

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Abstract

A model for thermal interactions of debris/water with gas flow from within and below debris bed was presented for severe accident analysis in LWR. The consumption of steam, production of hydrogen in the debris bed, generation of gases from below debris bed and generation of chemical heat are included in the conservation equations. The model has been incorporated in the MARCH code to estimate the gas production due to both metal/oxidation and hot debris/concrete interaction. The results indicate that the hydrogen source can potentially give a significant impact on the containment pressure transient and the conductive heat loss to concrete and the convective gas cooling in the debris bed have a smalle effect on the debris bed coolability. However, the reheating and melting of the debris particles could be delayed by the interaction of debris with concrete.

요 약

Debris bed내 · 외로 부터 깨스유량을 갖는 debris/water 열적상호작용 해석모델이 중대사고 분석을 위해 제시되었다. 제시된 모델은 증기 소비, debris bed에서 수소 생성, 유입깨스 및 화학반응열에 대한 인자들을 포함하고 있으며, 금속—물반응 및 debris/concrete 작용으로 인한 깨스 생성을 평가하기 위해 MARCH code에 도입시켰다. 그 결과 수소원은 격납용기 과도압력에 큰 영향을 미치나 debris bed로 대류깨스 냉각과 콘크리트로 전도 열손실은 debris bed 냉각성에 조그마한 영향을 주는 것으로 나타났다. 하지만 debris 인자의 재가열과 재용융은 콘크리트와 상호작용에 의해 상당히 지연될 수 있다.

Nomenclature

C_p	specific heat at constant pressure
D	average particulate diameter
g	acceleration of gravity
h	enthalpy
h_{lv}	heat of vaporization
L	bed depth
m	mass generation of consumption rate per unit volume
q	total heat transfer
s	saturation
T	temperature
V	superficial velocity
e	density
μ	dynamic viscosity
ε	bed porosity
σ	surface tension
θ	contact angle

Subscripts

d	debris particle
g	gas(1 : inflow, 2 : upflow)
l	liquid
m	gas-vapor mixtures
v	vapor
v'	superheated vapor
s	saturation

1. Introduction

The potential consequence of hydrogen production and the steam overpressurization have received increase attention in a recent year as a result of the Tree Mile Island-2 accident. Beyond design basis accident analyses has focused particularly on the hydrogen related problems and a spectrum of potential threats to the safety related equipment and containment structure. Therefore, there is need to accurately predict the non-condensable gas production (H_2, CO_2, Co, etc.) under severe accident conditions, and thus the analytical model for the thermal interactions between the core debris, water and gas is important for the application in LWR plant.

Considerable research has been performed to investigate the conditions that cause the particulate debris bed dryout behavior. Over last ten years experiments and modeling of the boiling and dryout in an internally heated porous bed have produced over fifty papers. None of these studies considered the combined mechanisms for the metal/water reaction, hydrogen production in the porous debris bed and gas generation from concrete decomposition. For the LWR application, Lipinski model[1)], which was chosen and modified in our work, appears to be the most widely accepted and its predictions agree well with the measured data, especially for large particles.

The containment behavior, that could finally result in core melt, has become a matter[2)] discussed frequently after the TMI-2 accident. It is important to establish the core debris cooling for evaluating the consequences of core degradation sequences in order to provide a more realistice assessment than the conservative, non-mechanistic evaluation that has been used in RSS study[3)]. One of the effort to develop an analytical tool for such hypothetical condition is MARCH computer code developed by BCL[4)]. The MARCH code models only the oxidation of the zircaloy cladding as the core heatup, melts and contacts steam in the vessel and in the reactor cavity, but not consider the steel-oxidation before molten debris/concrete interaction. The steel oxidation model presented by Yu[5)] during the above core meltdown stages indicated that the steel-steam reaction could potentially generate a significant quantity of hydrogen during ex-vessel core debris/water interaction. In this model[5] which is not related to the dryout model, all the spheres are assumed to be intimate contact with water and heat transfer between core debris and water is very high. Recently, Yang[6,7] presented the improved model for ex-vessel debris/water interaction with or without metal/water reaction. However, none of the above models considered the potential of the convective gas cooling in the core debris and of the conductive heat loss to concrete for the cooling of core debris. The previous paper[8] for debris/water/concrete interaction is only applied to the analysis of the effect of gas upflow but not consider the hydrogen production in the core debris bed. The metal oxidation model is not an integral part of the debris bed dryout model and appears to predict extremely high hydrogen generation rates under certain assumptions.

In the present paper, a debris bed model combining the metal/oxidation and gas upflow is suggested and incorporated into the MARCH code in a consistent manner for the thermal interactions between the core debris, water and gas.

2. Analytical Consideration

2.1. Metal/Oxidation

Hydrogen production may occur in copious quantities following a serious reactor incident which releases core debris from the vessel. It is interesting whether or not the short time in which bubbles containing steam are exposed to the steel is sufficient to reduce a major fraction of the steam to hydrogen. The progression of the accident depends on whether steam or hydrogen is added to the containment atmosphere. Two kinds of possible production processes are the zircaloy/steam and steel/steam reaction in a serious core damage accident. The following two reactions are considered:

$$\mathrm{Zr}+2\mathrm{H_2O}\longrightarrow \mathrm{ZrO_2}+2\mathrm{H_2}+Q_{Zr}$$

$$3\mathrm{Fe}+4\mathrm{H_2O}\longrightarrow \mathrm{Fe_3O_4}+4\mathrm{H_2}+Q_{Fe}$$

The energy release associated with the reaction is

$$Q_{Zr}=2912.5-0.058(+460),\ \text{Btu/lb Zr}$$

$$Q_{Fe}=457.2\ \text{Btu/lb Fe}$$

The zircaloy-steam reaction rate is given by the minimum of gaseous diffusion rate or solid state diffusion[9,10]. When core node drops into the bottom head, the zirconium cladding in this node, which is generally partially oxidiated may react further with the water in the bottom head. The metal/water reaction model assumes the debris is in the form of small spheres, the total area of all the spheres participates in the reaction, and the debris has an uniform temperature. The reaction rate is limited by the minimum of a solid state diffusion rate, a gaseous diffusion rate, or by the steam supply. The steam supply limitation is assumed to be determined by the boiling rate predicted by an isolated particle model, flat plate boiling rate, or by debris bed dryout model. The above metal/oxidation model is used to the combined debris bed model which will be described in the following section.

2.2. Gas Upflow from Below Core Debris

Most of the studies of the core/concrete interaction are limited to core debris in the molten state. There is only a few studies of the particulate debris interacting with the concrete. An experimental study of transient heat transfer in concrete was reported by Baker[10] for evaluating LMFBR molten core debris with water, and also Powers[11] has shown that there are three events, loss of evaporable water, loss of chemically constituted water, and loss of carbon dioxide, which depend on the decomposition temperature. According to the above situation, the gas upflow model considered in the previous paper[8] was used for analysis of the combined dryout model below.

2.3. Combined Dryout Model with Gas Inflow and Gas Upflow

The dryout heat flux model developed by Lipinski1) predicts boiling and dryout in a porous medium for the debris-water interaction. This model was based on a porous debris bed located in the reactor cavity with adiabatic and impermeable boundary between its core debris and concrete. For the thermal interactions of debris, water, and concrete, the gas flux model presented in the previous paper8) uses the conservation laws for mass, energy, and momentum with the adiabatic and permeable boundary conditions. Both of the model do not consider the influence of the metal/oxidation reaction for in-vessel and ex-vessel analysis. The metal/oxidiation model is not an integral part of the debris bed model and appears to predict extremely high hydrogen generation rates under certain assumptions. In this paper, the combined dryout model with metal/oxidation and with gas upflow has been studied.

In deriving these equations it has been assumed that the gas and vapor in the bed mix ideally within vapor flow channels, and that the inflowing and upflowing gas quickly come to temperature equilibrium with the bed. The liquid in the bed is described with a separate momentum equation. The momentum equation for two phase fluid counter-current flow through porous medium is12)

$$\frac{1.75(1-\varepsilon)\rho_m V_m^2}{d\varepsilon^3(1-S)^3}+\frac{150(1-\varepsilon)^2\mu_m V_m}{d^2\varepsilon^3(1-S)^3}+\frac{\Delta P_m}{L}+\rho_m g=0 \tag{1}$$

$$\frac{1.75(1-\varepsilon)\rho_1 V_1|V_1|}{d\varepsilon^3 S^3}+\frac{150(1-\varepsilon)^2\mu_1 V_1}{d^2\varepsilon^3 S^3}+\frac{\Delta P_1}{L}+\rho_1 g=0 \tag{2}$$

In the treatment of the oxidation process and concrete decomposition, the consumption of steam and the production gases are assumed additional mass sink and mass source terms in the continuity equation. The energy terms are included as additional heat sources in the particulate debris bed. The debris bed transfers heat such as decay heat, sensible heat, and chemical reaction heat to the fluid according to the boiling process in the porous medium. With the above assumptions, the conservation laws are modified as shown below. The continuity equation is

$$\rho_1 V_1+\rho_m V_m=m_{g_1}+m_{g_2}-m_v \tag{3}$$

The energy equation is

$$e_1 V_1 h_l+e_m V_m h_m=m_{g1}h_{g1}+m_{g2}h_{g2}-m_v h_v'+q \tag{4}$$

and

$$q=q_d+q_{g2}=q_d+\int_{T_s}^{T_g} e_{g2}C_{pg2}V_{g2}\Delta T$$

The mass, momentum and energy conservation equations can be combined to form an algebraic equation for bed saturation under the ediabatic and permeable boundary conditions:

$$\begin{aligned}&q^2[A_1A_4S^3+A_4(1-S)^3]\\&+q[A_1(2A_4A_6+A_2A_5)S^3\\&-(2A_4A_7-A_5)(1-S)^3]\\&+A_1A_1(A_4A_6+A_2A_5)S^3\\&+A_7(A_4A_7-A_5)(1-S)^3\\&-[(e_l-e_m)g+A_3]S^3(1-S)^3=0\end{aligned} \tag{5}$$

where, the setting value is

$$A_1=e_l/e_m$$

$$A_2=\mu_m/\mu_l$$

$$A_3=\frac{\Delta P_L-\Delta P_m}{L}=\frac{6\sigma(1-\varepsilon)\cos\theta}{\varepsilon dL}$$

$$A_4=\frac{1.75(1-\varepsilon)}{D\varepsilon^3 e_1 h_{1V}^2}$$

$$A_5=\frac{150(1-\varepsilon)^2\mu_1}{D^2\varepsilon^3 e_1 h_{1v}}$$

$$A_6=m_{g1}(h_{g1}-h_1)+m_{g2}(h_{g2}-h_1)-m_v(h_v'-h_1)$$

$$A_7=m_{g1}(h_m-h_{g1})+m_{g2}(h_m-h_{g2})-m_v(h_m-h_v')$$

The setting value terms and Equation (5) indicate the existence of the following relationship.7)

$$f(q, S, L, D, \varepsilon, m_{g1,\,g2,\,v},\ h_{g1,\,g2,\,v,\,v',\,l},\ \mu_{m,\,l}, e_{m,\,l})=0 \tag{6}$$

In the above Equation (6), the terms related to either metal/water reaction or concrete decomposition are ignored in case of completing either of them. The first two dependent parameters (q and s) determined from Equation (5) and the L value contains the independent parameter. The values, D and ε, are debris bed properities. The m terms represent the volumtric gas generation rate and steam consumption rate. They are considered to be explicit parameters in the numerical solution of Equation (5) and are provided at the previous time-step. The other parameters are properties of gas, vapor, and liquid of the water and are determined from the thermodynamic state of the fluids. As outlined by Lipinski[12], the treatment determines the onset of dryout in the debris bed. This is done by maximizing the total heat flux (q) with respect to variations of surface saturation (s). The heat transfer also determines the debris temperature which in turn controls the metal/water reaction rate and conductive heat loss rate. The combined model indicates that the effect of the upflowing gas is to always reduce the heat flux from the bed for a given saturation, thus always reducing the dryout heat flux. On the contray, the consumption of a large quantity of steam by the metal/water reaction enhances downward liquid flow into the debris bed and, hence, increases the heat transfer from the debris particles to fluid. The mass of steam consumed by the metal/water rebction is nine times more than hydrogen mass produced in the debris bed. The present model for the debris/water concrete interaction indicates that, until the core debris quenching, the hydrogen gas produced by metal/water reaction gives more impact on containment transient conditions than that of the unflow gas generated from below core debris bed.

3. Results

The debris bed model combining the metal/oxidation reaction and upflow gas is applied to a large dry pressurized water reactor containment. The gas production from the metal/water reaction and from below the core debris is investigated, and its impact on the cooling of core debris and containment pressure transient is also studied. The basic case considered is TMLB' accident sequence which is extended loss of AC power coupled with the failure of auxilary feedwater system. This case considers that there is 4.2×10^4 lbs. of zircaloy and 2×10^5 lbs. of steel in the reactor vessel, which are potentially available for oxidation during severe accidents. The concrete of limenstone aggregate used in this study, which is qualitatively similar basaltic type, is characterized by 80% calcium carbonate.

For the base case, it is assumed that the average particle size in the debris bed is 10mm and there is initially 4×10^5 lbs. of water in the reactor cavity. According to the MARCH calculation, the core slump occurs at 294 minutes. The hydrogen produced by the zircaloy-water reaction for the in-vessel case is about 1746 lbs., which is oxidized 95% of zirconium. The core drops into the reactor cavity after vessel failure and is assumed to form the particulate debris bed. As shown in Figure 1, the combined model predicts that, until the core debris quenching, 4,000 lbs. of hydrogen in the steel/water reaction are produced compared with 5,760 lbs. of H_2 if the modified Lipinski model[7] is used. The case of considering the decomposition reactioon is generated 400 lbs. of carbon dioxide and 1050 lbs. of evaporable-chemically consistituted water before debris reheat. The differences between two models are due to the steel oxidation and concrete decomposition as shown in Figure 1 and 2. Figure 2 illustrates that the variation time of oxidation reaction causes a large difference in hydrogen production. The modified model for debris/water

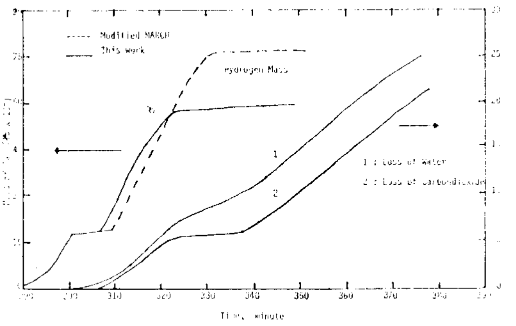

Fig. 1. Predicted Gas Mass Generated from Metal/Oxidation and Decomposition Concrete

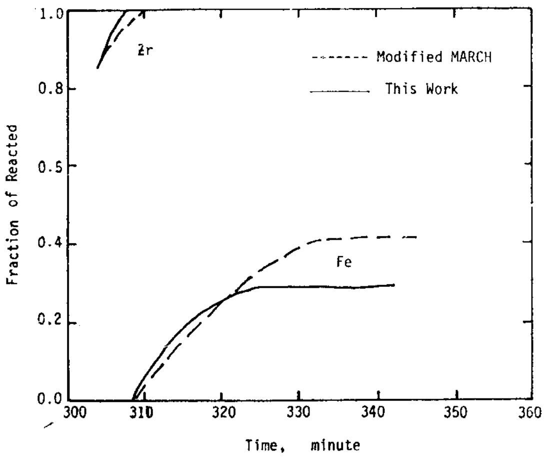

Fig. 2. Farction of Metal Reacted for Severe Accident Condition

interaction of 40% steel, while 28% of steel is oxidized in the case of the combined modelf or debris/water/concrete interaction. On the contrary, the BCL model[13], which the treatment between the debris bed model and the metal/water reaction is not taken in the unified manner, predicts approximately 70% of steam oxidation compared with the prsent model. The combined model predicts that about 10% of steel is reacted at the assumed 40mm particle sizes. This presents the higher dryout heat fluxes and rapid cooling of the debris particles in a small amoount of metal oxidation. In this event, the average saturation in the debris bed is about 50%. It seems that there is sufficient liquid penetrating into the porous bed for heat

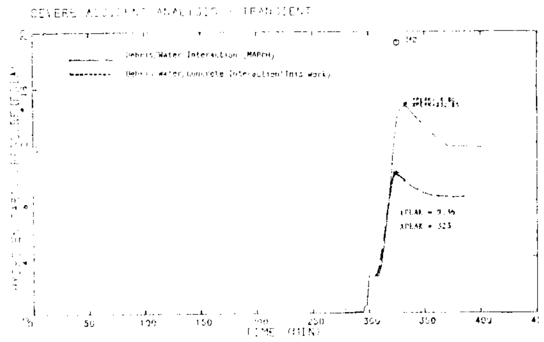

Fig. 3. Predicted Hydrogen Partial Pressure by Thermal Interaction

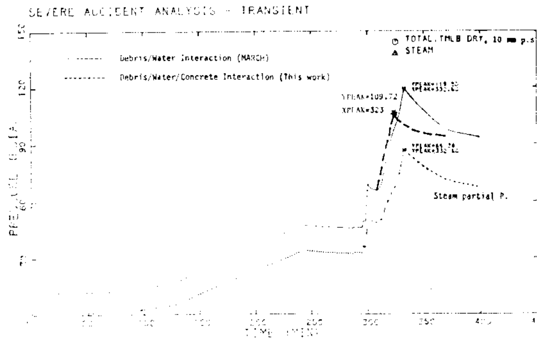

Fig. 4. Comparison of Containment Pressure Transient for TMLB'Dry Cavity

removal and the steam generation is sufficient to maintain the metal/water reaction prior to quenching of debris particles. Figure 3 shows the hydrogen partial pressure predicted by two models. About 6 psi differences between two models are due to the smaller oxidation which caused by quickly decreasing of the debris temprature and by the conductive heat loss to concrete. The impact of hydrogen release on the containment pressure transient is illustrated in Figure 4. The large amount of hydrogen predicted by the improved debris/water intraction yields peak pressure about 10 psi higher than that predicted by the present model. The steam partial pressure in the case of the combined model was about 66 psia at the time of debris quenching. Since the containment atmosphere is inerted by high steam mole fractions, hydrogen ignition and burning are not predicted for the case of TMLB' scenario. After ex-vessel boils off, the core debris is reheated until core debris is remelting. 2620 lbs. of evaporable-chemically constituted water and 2450 lbs. of carbon dioxide are generated, while concrete decompsition slowly increases. The water and carbon dioxide released during concrete decomposition are rapidly reduced to form hydrogen and carbon monoxide. The containment transient pressure during debris reheat slowly decreases until the condensation effect is higher than the effect on the decay heat and additional gas production.

The above reuslts present that the dryout heat flux in an uniform bed is predicted to increase with increasing particle diameters, with decreasing bed thickness and with decreasing gas flow and the small dryout heat flux leads to higher debris temperature. Especially, the dependency on all these parameters changes depending on whether the bed is channeled, moderately deep, or very deep. The assumed particle size must be accurately determined by experimental data since the debris particle size has an important effect on the inlet flow, such as the gases generated by the metal/oxidation and by the decomposition reaction. The convective gas cooling in the debris bed and the conductive heat loss to concrete yield a smalle effect on the debris bed coolability in the case of dry cavity. The hydrogen source, in addition to steam pressure spike, gives the additional impact on containment pressure transient.

4. Summary and Conclusions

1) The debris bed model with metal/oxidation and with upflow gas has been developed and incorporated into the MARCH code for the thermal interactions,

2) The gases produced by both of metal/oxidation and concrete decomposition decrease as the size of the debris bed particles increases,

3) The convective gas cooling in the debris bed and the conductive heat loss to concrete have a smalle effect on the debris bed coolability for the case of TMLB' dry cavity,

4) The hydrogen production predicted by the present model is considerably less than that predicted by the MARCH and modified debris bed model, and

5) The hydroogen source during core meltdown accident can potentially provide a significant on the containment pressure transient.

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