COOLING OF AN INTERNAL-HEATED DEBRIS BED WITH FINE PARTICLES

Z.L. Yang and B.R. Sehgal

Division of Nuclear Power Safety of Royal Institute of Technology, 10044 Stockholm, Sweden
E-mail: yang@ne.kth.se

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Abstract

In this paper, an analytical model on dryout heat flux of ex-vessel debris beds with fines particles under top flooding conditions has been developed. The parametric study is performed on the effect of the stratification of the debris beds on the dryout heat flux. The calculated results show that the stratification configuration of the debris beds with smaller particles and lower porosity layer resting on the top of another layer of the beds has profound effect on the dryout heat flux for the debris beds both with and without a downcomer. The enhancement of the dryout heat flux by the downcomer is significant. The efficiency of the single downcomer on the enhancement of the dryout heat flux is also analyzed. This, in general, agrees well with experimental data.

The model is also employed to perform the assessment on the coolability of the ex-vessel debris bed under representative accidental conditions. One conservative case is chosen, and it is found that the downcomer could be efficient measure to cool the debris bed and hence terminate the severe accident.

1 Introduction

Since TMI-2 accident, the cooling of a self-heated debris bed has been one of the most concerns in severe accident research of nuclear power plant. Numerous theoretical and experimental investigations have been performed to study the characteristics of two-phase flow and heat transfer in porous media. Significant progress has been obtained on the understanding and evaluation of dryout phenomenon in a self-heated porous debris bed under both top and bottom flooding conditions. Generally, it was found that the bottom flooding is a much more efficient cooling scheme than the top flooding. However, only top flooding can be employed as a passive severe accident management scheme. Lipinski correlation (Lipinski, 1982) was found to work well for predicting bed dry-out heat flux, with flooding, from top, of an one-dimensional debris bed. From which, it was found (Sehgal, et al., 1998) that a prototypic corium debris bed may not be coolable since a fine particle bed with low porosity could be obtained in melt-water interactions, as seen in the FARO experiments (Magallon, et al., 1999).

Experimental observations (Hofmann,1984, Becker et al, 1990) showed that significant enhancement of dryout heat flux can be obtained if a downcomer is installed. Recently, the experiment in RIT (Yang, et al. *1999*) also showed such a phenomenon. *Li* (*1999*) *tried to* quantify the dryout heat flux by employing a natural circulation scheme. However, their model does not allow the simulation of two-phase flow in fine particle (smaller than 2 mm) debris beds, in which the capillarity should be a factor in the enhancement mechanism of dryout heat flux.

In this paper, the model proposed by Li (1999) is improved. The capillary force is considered. The model is compared against the recent experimental data at RIT. The application of such a cooling scheme in a prototypic case is assessed.

2 Model formulation

Figure 1 shows a schematic view of the flow of liquid and vapor within the particulate debris beds with and without downcomer under the top flooding condition. The particulate debris beds may be both homogeneous and stratified. In stratified debris beds, small particles are assumed to rest on the top of large particle beds. The vapor channels are assumed to exist on the top of the bed where the particles have been pushed aside by the pressure in the vapor. Such channels are found to aid in vapor transport through that region. Right below the channel region, there is counter-current two-phase flow. Theoretically, for the particle beds without downcomer, as the heat generation in particle beds increases, the liquid fraction decreases. At some power, the vapor flow is great enough to reduce the downward flow of the liquid to the point where it all evaporates before it reaches the bottom of the bed. Below that point, the bed becomes dry. At this condition, the heat flux leaving the top of the bed is called dryout heat flux. For the beds with a downcomer, the water can penetrate into the beds from both top and bottom of the bed. The water flow rate penetrating into the top of the bed is limited by the counterflow of the vapor generated inside the bed. The water flow rate penetrating into the bottom of the bed depends on the capillary forces and the natural circulation capability established through downcomer and the bed because of the boiling inside the bed. At some power, all the water coming from the bottom evaporates at some position, and at the same time and at the same position, all of the down-flowing water also evaporates. At this moment, the dryout occurs.

The equations for steady-state energy and mass conservation for the beds with and without downcomer are the same, but with different boundary conditions on water flow rate at the bottom of the bed. The equations are

$$\frac{d}{dz}(\rho_v V_v h_{lv}) = Q \tag{1}$$

$$\frac{d}{dz}(\rho_v V_v + \rho_l V_l) = 0 \tag{2}$$

where ρ - density, V - superficial velocity, $h_l v$ - latent heat of vaporization, Q - local volumetric heat source. Index v and l correspond to vapor and liquid, respectively. Integrating Eqs. (1) and (2) leads to

$$\rho_v V_v h_{lv} = q \tag{3}$$

$$\rho_v V_v + \rho_l V_l = w \tag{4}$$

where q is the heat flux at the elevation z, w is the mass flux of liquid at the bottom inlet of the bed. For a uniform volumetric heat source Q, $q = Qz$. For the beds without downcomers, $w = 0$.

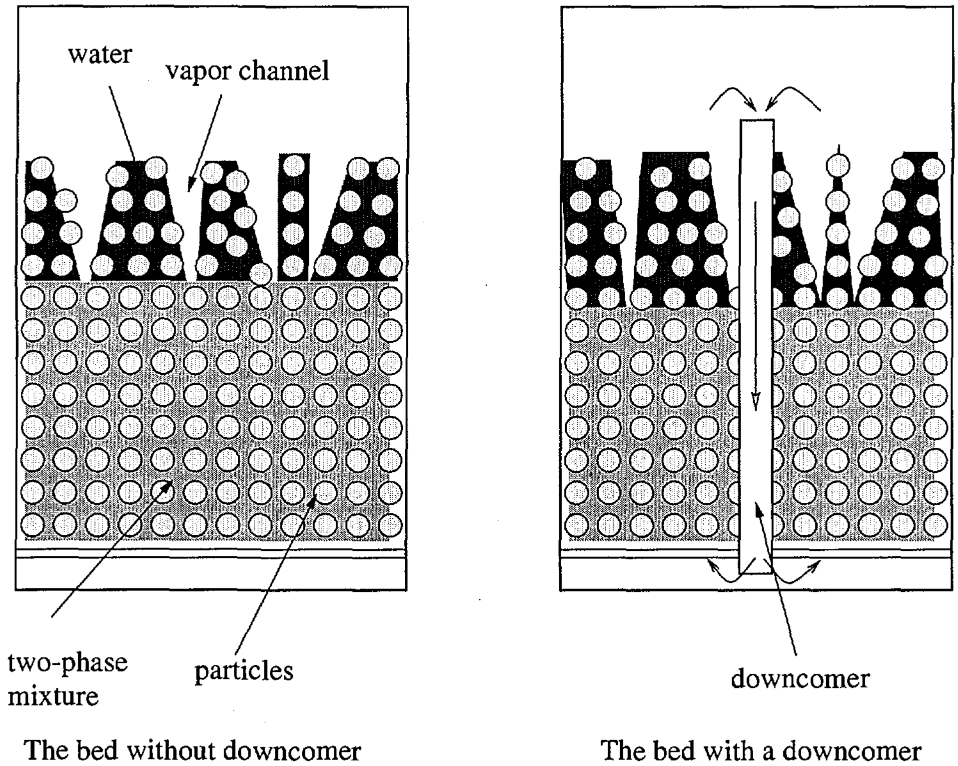

Figure 1: Schematic view of boiling and dryout in a bed of particulate debris.

The momentum conservation equations for both liquid and vapor take form of the extensions of the Ergun equation (Ergun, 1952). These equations were employed to analyze the dryout of a debris bed with top flooding by Lipinski (1983).

$$\frac{1.75(1-\epsilon)\rho_v V_v \mid V_v \mid}{\eta_v \epsilon^3 d} + \frac{150(1-\epsilon)^2 \mu_v V_v}{\kappa_v \epsilon^3 d^2} + \frac{dP_v}{dz} + \rho_v g = 0 \tag{5}$$

$$\frac{1.75(1-\epsilon)\rho_l V_l \mid V_l \mid}{\eta_l \epsilon^3 d} + \frac{150(1-\epsilon)^2 \mu_l V_l}{\kappa_l \epsilon^3 d^2} + \frac{dP_l}{dz} + \rho_l g = 0 \tag{6}$$

where ϵ - bed porosity, d - particle diameter, μ - dynamic viscosity, P - pressure, g - gravitational acceleration, κ - relative permeability, η - turbulent counterpart of κ. The relative permeabilities were found to be only the functions of effective saturation in the bed (Brooks, et al. 1966). The simplified forms for the relative permeabilities are

$$\kappa_v = (1-s)^3, \qquad \kappa_l = s^3 \tag{7}$$

$$\eta_v = (1-s)^5, \qquad \eta_l = s^5 \tag{8}$$

where s is the effective saturation. The difference between P_v and P_l is due to the capillary force and may be expressed in terms of a Leverett function J

$$P_v - P_l = \frac{\sqrt{150}\sigma(1-\epsilon)cos\theta J}{\epsilon d} \tag{9}$$

where the Leverett function is

$$J = \frac{(s^{-1} - 1)^{0.175}}{\sqrt{5}} \tag{10}$$

Combining Equation (3) through (9), we have a single first-order differential equation:

$$\frac{\sqrt{150}\sigma(1-\epsilon)cos\theta}{\epsilon d}\frac{dJ}{ds}\frac{ds}{dz} + \sqrt{150}\sigma(1-\epsilon)cos\theta J\frac{d}{dz}(\frac{1-\epsilon}{\epsilon d}) - (\rho_l - \rho_v)g + \frac{1.75(1-\epsilon)q^2}{h_{lv}^2\epsilon^3 d}\left[\frac{1}{\rho_v(1-s)^5} \pm \frac{1}{\rho_l s^5}\right] + \frac{150(1-\epsilon)^2 q}{h_{lv}\epsilon^3 d^2}\left[\frac{\mu_v}{\rho_v(1-s)^3} + \frac{\mu_l}{\rho_l s^3}\right] + \frac{(1-\epsilon)w}{\rho_l\epsilon^3 d}\left[\pm\frac{1.75w}{s^5} \mp \frac{3.5q}{s^5 h_{lv}} - \frac{150(1-\epsilon)\mu_l}{s^3 d}\right] = 0 \tag{11}$$

where the upper sign applied for $q > wh_{lv}$ and the lower sign applied for $q < wh_{lv}$. All bed properties can be functions of the elevation, so the equation is valid for both uniform and stratified debris beds, where the particle diameter, porosity, and the volumetric heat source can vary with the elevation.

Equation (11) is applied only to the packed boiling region of the bed. A top boundary condition must be used to accommodate channels, which can form on the top of the debris bed, especially for the the beds with fine particles resting on the top, because of the boiling. Near the top of the bed, there is insufficient pressure from the weight of the bed, and the vapor may push back both the liquid and the particles. The formation of channels allows the orderly flow of liquid going downward between the channels and vapor going upward within the channels. Lipinski (1983) developed a model to estimate the channel length and the saturation at the base of the channel. In his model the vapor pressure at any location in the channel is assumed to be sufficient to offset the weight of the overlying particles plus the liquid. Equation (9) was used to determine the vapor pressure at the base of the channels, and the liquid pressure is assumed to be hydrostatic. The continuity of pressure then yields a criterion for the channel length

$$L_c = \frac{\sqrt{150}\sigma cos\theta J}{(\rho_p - \rho_l)g\epsilon d} \tag{12}$$

where ρ_p is the particle density. According to the pressure gradient continuity at the base of the channels, using Equations (3), (5), (7) and (8), with an expression for bed pressure, the following condition is obtained

$$\frac{(1-\epsilon)q_c}{\rho_v g h_{lv}\epsilon^3 d}\left[\frac{1.75q_c}{(1-s)^5 h_{lv}} + \frac{150(1-\epsilon)\mu_v}{(1-s)^3 d}\right] = (1-\epsilon)\rho_p + \epsilon\rho_l \tag{13}$$

where q_c is the heat flux at the base of the channeled region. Since q_c is a function of L_c, Equation (12) and (13) must be solved simultaneously to obtain the channel length and saturation at the top of the packed boiling zone, which sets boundary conditions for Equation (11).

For the bed without the downcomer, the distribution of the saturation in the packed debris bed (no channels) can be obtained by solving Equations (11) (12) and (13) with the boundary condition of $w = 0$. For the bed with a downcomer, an additional condition has to be provided to obtain w. The mass flux at the bottom of the debris bed is dependent on the natural circulation capability, in which the capillary force inside the bed should strengthen the natural circulation.

The total pressure drop in such a natural circulation loop includes friction pressure drop in the downcomer ΔP_d, the liquid pressure drop in the debris bed ΔP_b, the friction pressure drop between the outlet of the downcomer and the bottom surface of the debris bed ΔP_{in}, and the friction pressure drop between the inlet of the downcomer and the top surface of the debris bed ΔP_{out}. The total driving head of the system includes the gravitational driving head H_g and the capillary force head in the debris bed H_c. The total pressure drop in debris bed ΔP_b can be obtained by integrating Equation (6)

$$\Delta P_b = \int_0^Z \frac{dP_l}{dz} dz = \int_0^Z \left[-\frac{1.75(1-\epsilon)\rho_l V_l \mid V_l \mid}{\eta_l \epsilon^3 d} - \frac{150(1-\epsilon)^2 \mu_l V_l}{\kappa_l \epsilon^3 d^2} - \rho_l g \right] dz \tag{14}$$

where Z is the height of the packed debris bed. The friction pressure drop in the downcomer is

$$\Delta P_d = \int_0^H \left[\frac{2 f w^2}{\rho_l D_{down}} \left(\frac{A_b}{A_{down}} \right)^2 \right] dz \tag{15}$$

where f is the friction coefficient, and it depends on the Reynold number of liquid flow in the downcomer: $f = cRe_l^{-n}$. For laminar flow, $c = 16$ and $n = 1$, for turbulent flow, $c = 0.046$ and $n = 0.2$. The friction pressure drops in between the downcomer and particulate bed are assumed small and neglected.

The total driving force is expressed as

$$\Delta P_{drive} = \int_0^Z \left[\rho_l g + \frac{\sqrt{150}\sigma(1-\epsilon)cos\theta}{\epsilon d} \frac{dJ}{dz} \right] dz \tag{16}$$

According to the rule of the natural circulation, we should have

$$\Delta P_{drive} = \Delta P_d + \Delta P_b \tag{17}$$

Combining Equations (11) and (17), we can find the solutions for the distribution of saturation s in the bed and the liquid mass flux at the bottom of the bed w. The heat flux at the top of the debris bed, then, can obtained, as the dryout heat flux once the dryout is observed at some location at some power level in the debris bed.

3 Results and discussion

In this section, a parametric study based on the present model is performed only for the stratified particle beds with a downcomer. The focus is on the particle beds with fine particles. The effects of downcomer, particle beds stratification are investigated. The calculation is also compared against the experiments performed in RIT. Finally, the potential application of downcomer for the ex-vessel corium debris bed coolability is assessed.

3.1 Parametric effects

3.1.1 Stratification

Firstly, the effect of the stratification of the particulate debris beds is investigated. The total debris bed height is 370 mm. For the bottom layer, the particle size is 0.92 mm in diameter, the porosity is 0.365. For the top layer, the particle size is 0.8 mm in diameter, the porosity is 0.258. The cross-section area of the debris bed is 0.1225 m^2. The top layer of the particle bed has smaller particles and lower porosity. The ratio of the heights is that of the top layer to the bottom layer.

Figure (2) shows the calculated results on the dryout heat flux for the beds with and without a downcomer, which has 30 mm in diameter and 500 mm in height. Both curves show the same tendency that the bed with a thicker top layer has lower dryout heat flux. The calculation shows that the downcomer improves the dryout heat flux more than 100% for all range of the stratification (the thickness ratios) calculated. For the beds with thicker layer of the smaller particles and lower porosity (the ratio > 1.0), the dryout heat flux has little changes, especially for the bed without downcomer, in which both the counter-current two-phase limitation and the factor of capillary force in top layer particles dominate the process. However, when the thickness of the top layer is small, the effect of the bottom layer particles is becoming large. When the thickness of top layer is extremely small (less than 10 percent), the channeling effect in the top layer will immune the role of the top layer particle in governing the dryout process. The dryout heat flux will be dependent mostly on the geometrical configuration of bottom layer particle, which has much high dryout heat flux.

For the beds with a downcomer, the general behavior of the dryout heat flux variation with the thickness ratios is similar to that of the beds without downcomer. However, the geometrical configuration of bottom layer particles has larger effect on the dryout heat flux when the thickness ratio is small, since it effects both the general capillary forces in the beds and thermal hydraulic of the water in the bed, so as to the water mass flux from the bottom of the beds.

Figure (3) shows the enhancement of the dryout heat flux by a downcomer for the same particle debris beds. The enhancement of the dryout heat flux is expressed as

$$Q_{enhance} = \frac{q_{down} - q_{no-down}}{q_{no-down}} \tag{18}$$

It can be seen that the thicker the top layer of the debris beds is, the smaller the enhancement of the dryout heat flux is achieved by a downcomer.

Note that the present model for top flooding without a downcomer was well validated against experimental data for homogeneous beds with both large and fine particles. However, little experimental data can be found for the dryout heat flux of the stratified particle beds with fine particles on the top.

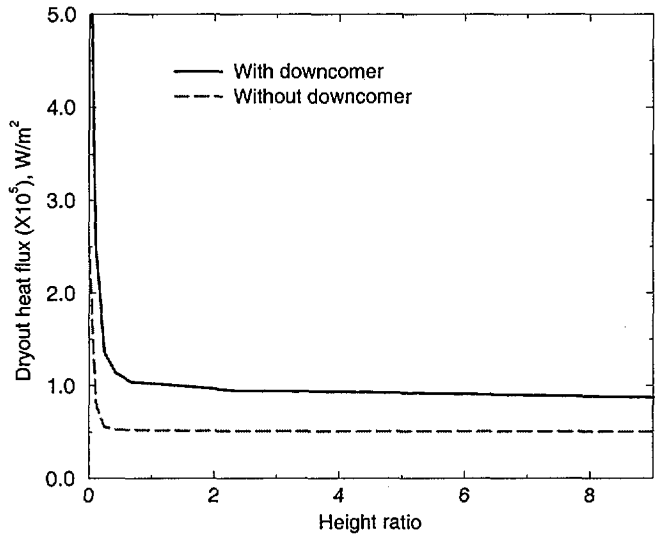

Figure 2: The effect of the thickness ratio of top to bottom layer of different particles.

3.1.2 Porosity of top layer particles

The porosity of the top layer of the particle debris beds is one of the very important factors for the dryout heat flux, especially for the top flooding. Figure (4) shows the calculated results of dryout heat flux of the stratified particle beds with and without a downcomer. The bottom layer of the beds is 240 mm thick, and is composed of the particles of 0.92 mm in diameter, the porosity is 0.365. The top layer of the beds is 130 mm thick, and is composed of the particles of 0.8 mm in diameter, the porosity is varied from 0.15 to 0.365.

The calculated results show that the dryout heat fluxes for the beds both with and without a downcomer increase with the porosity of the top layer of the beds. The enhancement of the dryout heat flux is shown in Figure (5). Three different regions are observed. The first is that the porosity of the top layer particles is less than 0.22, the enhancement of dryout heat flux by a downcomer is about 0.80. The second region is that the porosity is varied from 0.22 to 0.27, the enhancement of the dryout heat flux increases linearly from 0.80 to 1.60. The third region is that the porosity is larger than 0.27, the enhancement of the dryout heat flux by a downcomer is about 1.60. For the first region, since the porosity of the top layer debris is very low, the frictional pressure drop of the two-phase flow is very large, the capillary force is a dominant force to sock the water from the bottom into the beds. However, when the porosity of the top layer increases, the frictional pressure drop of the two-phase flow decreases, the gravitational drive head starts to contribute the natural circulation of the system.

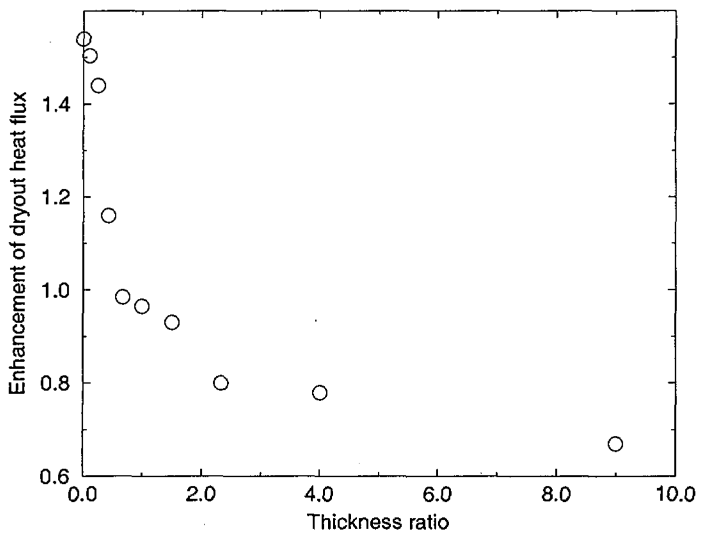

Figure 3: The enhancement of the dryout heat flux by a downcomer.

3.1.3 Efficiency of single downcomer

The efficiency of the downcomer on the enhancement of the dryout heat flux is also investigated. A stratified bed is chosen with the variation of the cross-section area of the debris bed. The rest of the parameters of the debris bed configuration remained un-changed. The total debris bed height is 370 mm. The height of the bottom layer is 130 mm, the particle size is 0.92 mm in diameter, the porosity is 0.365. The height of the top layer is 240 mm, the particle size is 0.8 mm in diameter, the porosity is 0.258. The cross-section area of the debris bed is varied from 0.1 m^2 to 6 m^2. Only onle downcomer is considered in such debris beds. The downcomer is 30 mm in diameter and 500 mm in height.

Figure (6) shows the calculated results on the variation of the dryout heat flux with the area of the debris beds with one downcomer installed. It can be seen that the dryout heat flux has little change for the beds with the area up to 2 m^2. The dryout heat flux decreases only 20 percent for the beds with the area from 2 m^2 to 6 m^2. This indicates that if the debris bed area is not so large and the water can easily access to any place of the bottom surface of the debris bed, the mass flow rate of water inside the downcomer is small, the frictional pressure drop, therefore, is small and has little effect on the natural circulation of the water in such a system. The two main driving pressure heads - capillary force and gravitational head - are practically independent of the bed area and the diameter of the downcomer. If the diameter of the downcomer is not small, the geometry of downcomer has little effect on the dryout heat flux. However, if the area of the debris beds is large, the water flow rate may be very high in the downcomer, the frictional pressure drop in the downcomer becomes larger, and the flow rate of water then decreases, so as to the dryout heat flux. It can also be concluded that if the area of the debris bed is less than 2 m^2, the increase of the number of the downcomers of 30 mm in

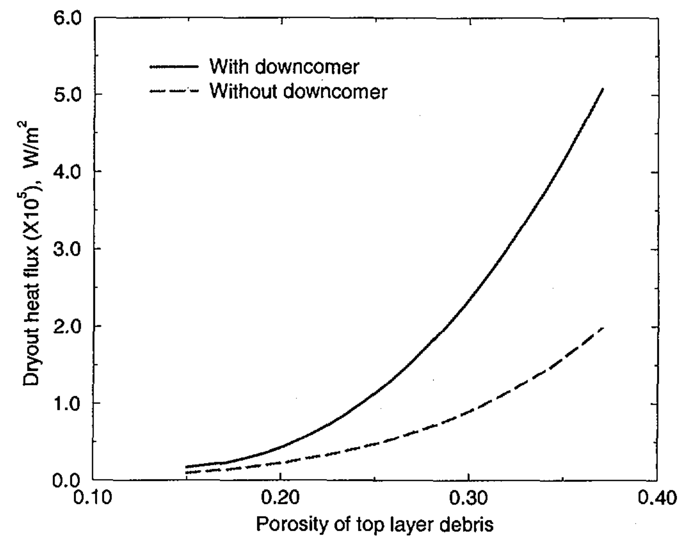

Figure 4: The effect of porosity of top layer particles.

diameter has little effect on the enhancement of dryout heat flux.

3.2 Comparison with experimental results

The present model is employed to analyze the experimental data obtained in RIT (Yang, et al. 1999). The experiments were performed in a 350 × 350 × 500 mm test section. The particle beds are 350 × 350 in cross section and 370 mm in height. The mean particle diameters varied from 0.198 mm to 2 mm, the porosity varied from 0.258 to 0.39. The effect of a downcomer, which is 500 mm in height and 30 mm in diameter, on the dryout heat flux is also tested. The experimental results show that the downcomer significantly enhanced the dryout heat flux in comparison with the case of the top flooding for both homogeneous and stratified particle beds.

Figure (7) shows the comparison of calculated results with experiments [10]on the enhancement of the dryout heat flux by a downcomer. It can be seen that some results underpredict the experimental results, some agree well with the experiments, and some overpredict the experimental results, for both homogeneous and stratified beds. Generally, the calculated results show that the enhancement of the dryout heat flux is greater than 60 percent for all the debris beds tested in the experiments (Yang, et al. 1999), this is coincided with the experiments.

The difference between the present calculation and the experimental results may be explained by the following:

(1) The empirical correlations employed in the model were validated against the data from the sphere particle beds. The effect of the irregularity of the particle is not clear.

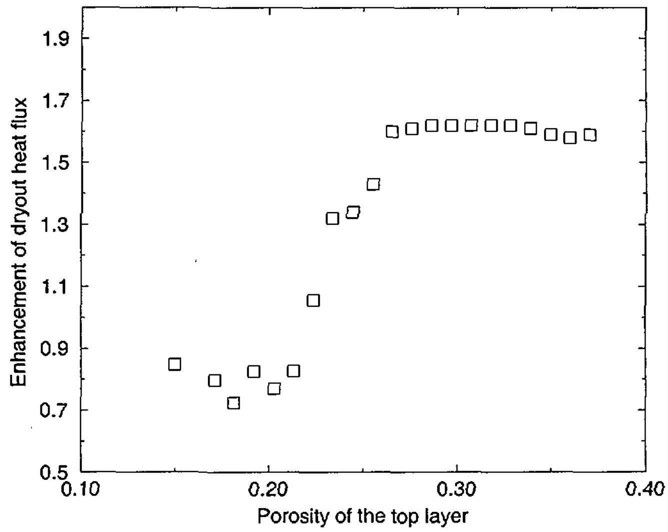

Figure 5: The enhancement of the dryout heat flux by a downcomer.

(2) The model is one-dimensional, the debris beds employed in the experiments are, certainly, three dimensional in both particle size distribution and porosity, which may significantly effect the dryout heat fluxes for both homogeneous and stratified beds.

(3) There may be some uncertainties of the evaluation of the mean particle sizes and the porosity of the particulate debris beds employed in the experiments.

3.3 On the application of the downcomer in ex-vessel debris coolability

The Swedish BWRs employ a deep pool in the lower dry well as a severe accident management scheme to cool the melt discharged from the failed vessel. In the absence of a steam explosion, a deep debris bed may result, which maybe composed of a melt layer topped by a crust, and a particle bed, resting on it. The particle bed will have a gradation of particle sizes, with smaller size particles forming the very top layers, since they will be levitated by the steam produced during melt-water interaction event depositing later on the bed. FARO tests (Magallon, et al., 1997) showed that the interaction between the corium and subcooled water could result in the debris bed with mean particle size less than 2.5 mm, and more than 10 percent of the particles might be smaller than 1 mm. However, no porosity measurement for debris beds was performed in all the FARO tests.

In present study, a conservative case is chosen to evaluate the downcomer performance for the ex-vessel debris coolability of a medium power level BWR. In this case, all the reactor core material is released into the reactor cavity. No steam explosion is assumed to occur. After the fragmentation, a 350 mm thick debris may be formed. The debris bed is stratified. The top layer of the debris bed is 50 mm in thickness, the porosity is about 0.30, the mean particle size

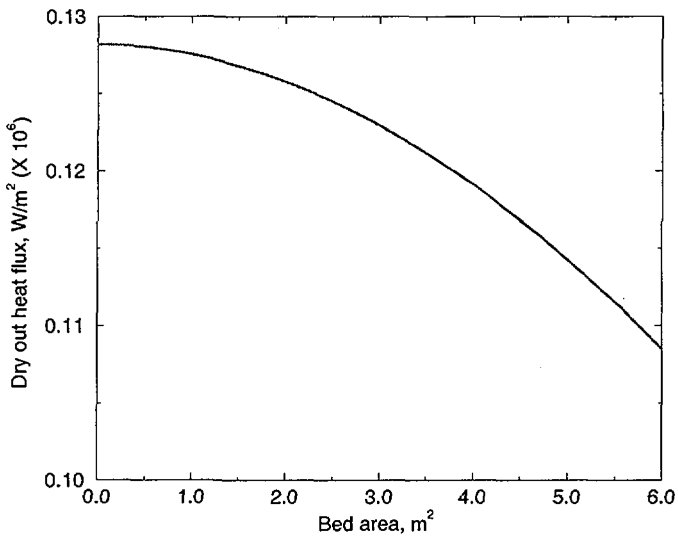

Figure 6: The effect of cross section area particulate debris bed.

is about 1.0 mm. The bottom layer of the debris bed is 300 mm in thickness, the porosity is about 0.40, the mean particle size is about 2.0 mm. The decay heat generation is about 1 MW per cubic meter of the debris material, so the heat generation inside of the debris bed is about 0.6 - 0.7 MW/m^3. A debris bed of 1 m^2 is considered. The downcomer is 50 mm in diameter and 500 mm in height.

The calculation shows that the dryout heat flux for such a debris bed without downcomer is about 0.136 MW/m^2, which is equivalent to 0.39 MW/m^3 of the heat generation rate in the debris bed, and to 0.6 MW per cubic meter of the debris material. This shows that the top flooding may not cool the debris bed. The calculation also shows that the dryout heat flux for such a debris bed with a downcomer is about 0.344 MW/m^2, and this is equivalent to 0.98 MW/m^3 of heat generation in the debris bed and to 1.5 MW per cubic meter of the debris material. This is about 50% higher than the decay heat in the corium.

In the prototypic cases, the debris beds will not be ideal one-dimensional stratified bed. If the amount of the corium discharged from the vessel is small, the debris may, most probably, be like a mountain. The three-dimensionality of the debris bed will greatly improve the coolability of the debris bed even for the top flooding conditions. However, the most inner part of the debris may still not be quenched. In this case, the downcomer may be the solution.

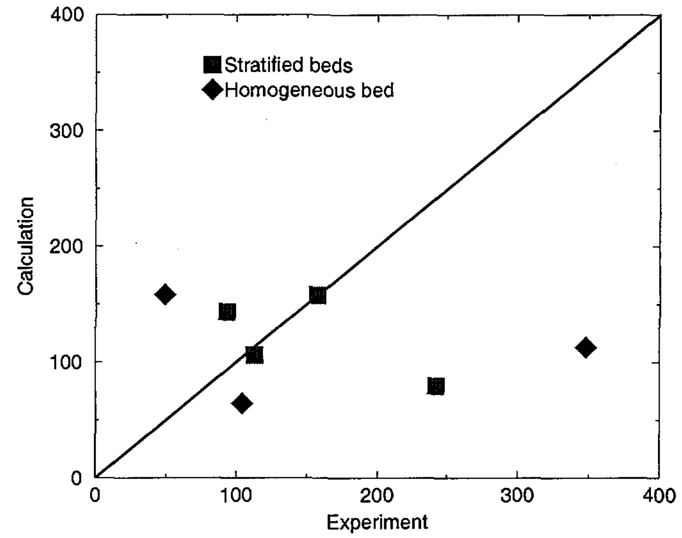

Figure 7: The comparison of calculated results with experiment on the enhancement of the dryout heat flux by a downcomer.

4 Concluding remarks

In this paper, an analytical model on dryout heat flux of a particulate debris bed under top flooding conditions has been developed. The model allows to analyze the dryout phenomenon in a porous debris bed both with and without a downcomer. The focus of this model is on the effect of the fine particles on the dryout heat flux, in which the capillary force is an important factor. The stratification of the debris beds is also considered in the model.

The parametric study, however, is focussed on the effect of the stratification of the debris beds on the dryout heat flux. The calculated results show that the stratified configuration of the debris beds with smaller particles and lower porosity layer resting on the top of another layer of the beds has profound effect on the dryout heat flux for the debris beds both with and without a downcomer. The same tendency is observed for the variation of the dryout heat flux with the thickness ratio of the top layer to bottom layer particles for the beds both with and without a downcomer. When the thickness of the top layer particle is small, the dryout heat flux is very sensitive to the thickness ratio. However, when the top layer particle is thick, the dryout heat flux has little change with the thickness ratio. The calculated results also show that the thicker the top layer of the debris beds is, the smaller the enhancement of the dryout heat flux is achieved by a downcomer.

The calculated results show that the dryout heat fluxes for the beds both with and without a downcomer increase with the porosity of the top layer of the beds. Three different regions on the enhancement of the dryout heat flux by a downcomer are observed. These different regions is coincided with the role of different forces in the natural circulation of the system.

The efficiency of the single downcomer on the enhancement of the dryout heat flux is also analyzed. It is found that if the diameter of the downcomer is not small (larger than 30 mm in diameter), the geometry of downcomer has little effect on the dryout heat flux of the debris beds whose area is less than 2 m^2. In this case, the increase of the number of the downcomers of 30 mm in diameter has little effect on the enhancement of dryout heat flux.

The present calculation is compared with experimental results (Yang, et al. 1999) on the enhancement of the dryout heat flux by a downcomer. The calculation results show that the enhancement of the dryout heat flux is higher than 60 percent for all the debris beds tested in the experiments (Yang, et al. 1999), this is coincided with the experiments.

Finally, the model is employed to perform the assessment on the coolability of the ex-vessel debris beds under prototypic accidental conditions. One conservative case is chosen, and it is found that the downcomer may be an efficient measure to cool the debris beds, and hence to terminate the severe accident.

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