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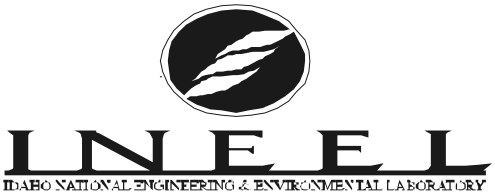

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SCDAP/RELAP5 MODELING OF FLUID HEAT TRANSFER AND FLOW LOSSES THROUGH POROUS DEBRIS IN A LIGHT WATER REACTOR

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ABSTRACT

The SCDAP/RELAP5 code is being developed at the Idaho National Engineering and Environmental Laboratory under the primary sponsorship of the U. S. Nuclear Regulatory Commission (NRC) to provide best-estimate transient simulations of light water reactor coolant systems during severe accidents. This paper describes the modeling approach used in the SCDAP/RELAP5 code to calculate fluid heat transfer and flow losses through porous debris that has accumulated in the vessel lower head and core regions during the latter stages of a severe accident. The implementation of heat transfer and flow loss correlations into the code is discussed, and calculations performed to assess the validity of the modeling approach are described. The different modes of heat transfer in porous debris include: (1) forced convection to liquid, (2) forced convection to gas, (3) nucleate boiling, (4) transition boiling, (5) film boiling, and (6) transition from film boiling to convection to vapor. The correlations for flow losses in porous debris include frictional and form losses. The correlations for flow losses were integrated into the momentum equations in the RELAP5 part of the code. Since RELAP5 is a very general non-homogeneous non-equilibrium thermal-hydraulics code, the resulting modeling methodology is applicable to a wide range of debris thermal-hydraulic conditions. Assessment of the SCDAP/RELAP5 debris bed thermal-hydraulic models included comparisons with experimental measurements and other models available in the open literature. The assessment calculations, described in the paper, showed that SCDAP/RELAP5 is capable of calculating the heat transfer and flow losses occurring in porous debris regions that may develop in a light water reactor during a severe accident.

NOMENCLATURE

α_f	=	volume fraction of liquid phase,
α_g	=	volume fraction of vapor in fluid,
α_l	=	threshold void fraction for inverted annular flow,
A_s	=	surface area of debris per unit volume (m^2/m^3),
ε	=	porosity of debris,
δ	=	vapor film thickness (m),
β	=	volume coefficient of expansion of vapor (1/K),
c_g	=	heat capacity of vapor (J/kg · K),
D_b	=	bubble diameter (m),
D_p	=	effective diameter of debris particle (m),
g	=	acceleration of gravity (m/s^2),
h	=	convective heat transfer coefficient (W/m · K),
h_{fg}	=	latent heat of vaporization (J/kg),
k_g	=	thermal conductivity of vapor (W/m · K),
ρ_f	=	density of liquid (kg/m^3),
ρ_g	=	density of vapor (kg/m^3),
Q_{conv}	=	heat transferred to vapor by convection (W/m^3),
Q_{rad}	=	heat transferred to vapor by radiation (W/m^3)
ν_g	=	vapor velocity (m/s),
μ_g	=	vapor viscosity (kg/m · s),
ΔT	=	local temperature difference between debris and vapor ($T_d - T_g$),
ΔT_{sub}	=	difference between saturation temperature of the liquid and the pool or free stream temperature (K),
ΔT_w	=	difference between the temperature of the debris particles and the saturation temperature of the liquid (K),
σ	=	surface tension (N/m).

INTRODUCTION

The SCDAP/RELAP5 code has been developed for best estimate transient simulation of light water reactor coolant systems during a severe accident. It is the result of merging detailed SCDAP core damage progression models with the

RELAP5/MOD3 thermal-hydraulics code modeling capabilities, to produce a powerful detailed modeling capability that is unparalleled. The code models the coupled behavior of the reactor coolant system and the reactor core. Variables important for accident analysis that are calculated by the code include; (1) reactor primary and secondary coolant system pressures, (2) water inventory in the reactor primary and secondary coolant systems, (3) heat up and damage to reactor core, (4) amount of hydrogen production, (5) amount of melted core material, (6) amount of fission product release, and (7) extent of structural damage to reactor system components such as the surge line and reactor vessel lower head. In addition to analyzing severe accidents, the code is also applicable to the analysis of large and small break loss of coolant accidents, operational transients such as an anticipated transient without SCRAM, loss of offsite power, loss of feedwater, and loss of flow. A generic modeling approach is used that permits as much of a particular system to be modeled as necessary. Control system and secondary system components are included to permit modeling of plant controls, turbines, condensers, and secondary feedwater conditioning systems.

This paper describes models implemented into the code to calculate heat transfer and flow losses in regions of the core and lower head following the formation of porous debris during the late phases of a severe accident. The focus of the paper is on the theoretical modeling, and the implementation and testing of models used to verify debris bed thermal-hydraulic behavior.

2. Modeling of Debris Bed Heat Transfer

Previous SCDAP/RELAP5 code versions included the capability to model convection and radiation heat transfer from the surfaces of nonporous debris in a detailed manner and to model only in a simplistic manner the heat transfer from porous debris. In order to advance beyond the simplistic modeling of porous debris heat transfer, applicable porous debris heat transfer correlations were incorporated into the code for (1) forced convection to vapor, (2) forced convection to liquid, (3) nucleate boiling, (4) transition boiling, (5) film boiling, and (6) transition from film boiling to convection to steam. The regimes of convective heat transfer are distinguished by the values of two parameters: (1) volume fraction of liquid in the open porosity of the debris bed, and (2) temperature of the debris. The regimes of heat transfer range from nucleate boiling in two-phase coolant to natural convection in steam. The various regimes of convective heat transfer and the corresponding ranges in values of volume fraction of liquid and debris temperature are described in more detail in Reference 1.

2.1 Single Phase Vapor Debris Bed Heat Transfer

The heat transfer correlation developed by Tung is used to calculate the debris-to-vapor convective heat transfer. In this correlation, the Nusselt number is given by the equation

$$Nu_{conv} = 0.27Re^{0.8}\, Pr^{0.4} \quad (1)$$

where

Nu_{conv} = Nusselt number for convection $(hD_p)/k_g$,

Re = Reynold's number $(\rho_g \upsilon_g D_p / \mu_g)$,

Pr = Prandtl number $(\mu_g c_g / k_g)$.

For the case of low fluid velocity, the Nusselt number for natural convection is calculated. If the Nusselt number for natural convection is greater than that for forced convection, then the natural convection Nusselt number from Edwards, Denny and Mills[13] is applied as

$$Nu_{nat} = KRa^{0.25} \quad (2)$$

where

$$K = \begin{cases} 0.3 & 0 \le Ra \le 50 \\ 0.4 & 50 \le Ra \le 200 \\ 0.5 & 200 \le Ra \le 10^6 \\ 0.6 & 10^6 \le Ra \le 10^8 \end{cases}$$

and the Rayleigh number (Ra) is

$$Ra = \frac{\rho_g^2 g D_p^3 \beta (T_D - T_g)}{\mu_g^2}.$$

The heat transferred by natural or forced convection is then given by

$$Q_{conv} = A_s \max (Nu_{conv}, Nu_{nat}) \frac{k_g}{D_p} (T_D - T_g) \quad (3)$$

The total heat transferred by natural or forced convection is then added to the heat transferred by radiation to the vapor to obtain the total heat transfer to vapor.

$$Q = Q_{conv} + Q_{rad} \quad (4)$$

2.2 Single Phase Liquid Debris Bed Heat Transfer

The heat transfer correlation presented by Gunn[15] is used to calculate the volumetric heat transfer coefficient for the covered regime. This correlation is applicable for water that is either subcooled or saturated. The correlation for the Nusselt number in this case is given by the equation

$$Nu = (7 - 10\varepsilon + 5\varepsilon^2)(1 + 0.7Re^{0.3}\, Pr^{0.333}) \quad (5)$$

$+(1.33 - 2.4\varepsilon + 1.2\varepsilon^2)\, Re^{0.7}\, Pr^{0.333}$

The volumetric heat transfer coefficient is then calculated by the equation

$$h_v = Nu \frac{k_f}{l^2}, \qquad (6)$$

where l is the characteristic length defined by Gunn.[15] The total heat transferred to the liquid is calculated by the equation

$$Q = h_v (T_D - T_f) \qquad (7)$$

2.2 Two-Phase Flow Debris Bed Heat Transfer

The debris-to-fluid heat transfer in the two-phase region is a complex process. The heat transfer modeling is made to be consistent with the flow regime modeling. In view of the fact that there is an absence of available experimental data and theoretical models for local heat transfer coefficients for two-phase conditions, a simplified approach is required.

Four modes of convective heat transfer are considered: (1) nucleate boiling; (2) film boiling; (3) transition boiling; and (4) transition from film boiling to convection to vapor. The mode of heat transfer that is in effect is a function of the debris temperature and the volume fraction of vapor in the fluid. The range of conditions for each mode of heat transfer has been summarized in Reference 1.

2.2.1 Nucleate Boiling

The heat transfer coefficient for nucleate boiling is calculated by a correlation for pool boiling that was developed by Rohsenow[16] and used by Tutu[24], et al. This correlation is

$$h_{snuc} = 4.63 \times 10^6 f(prop)(T_D - T_{sat})^m \qquad (8)$$

where f(prop) is a function of fluid properties.[16]

The exponent is calculated by the equation

$$m = 3.3 - 9.0e^{-d} \qquad (9)$$

where

$$d = \left\{ \frac{D_p}{\left[\frac{\sigma}{g(\rho_f - \rho_g)} \right]^{0.5}} \right\}^{0.5}.$$

2.2.2 Film Boiling

The correlation developed by Dhir and Purohit[18] is used to calculate the surface heat transfer coefficient for the film boiling mode of heat transfer. According to their correlation, the Nusselt number is calculated by the equation

$$Nu = \frac{hD_p}{k_g} =$$

$$\overline{Nu_0} + \overline{Nu_{nc}} \frac{Pr_g\, Sc}{Pr_f\, Sh \mu_f} + \frac{Pr_g}{Sh} \frac{\sigma(T_w^4 - T_{sat}^4) D_p}{h_{fg} \mu_g} \qquad (10)$$

where

$$\overline{Nu_0} = 0.8 \left[\frac{g\rho_g(\rho_f - \rho_g) h_{fg} D_P^3}{\mu_g k_g \Delta T_w} \right]^{1/4} \text{ and}$$

$$Nu_{nc} = 0.9 \left[\frac{g\rho_f^2 - C_{pf} \beta \Delta T_{sub} D_p^3}{\mu_f k_f} \right]^{1/4}.$$

The equation for Nu_0, as defined in Reference 18, includes the energy transfer by conduction and radiation across the film. The energy transferred by radiation is generally about **10%** of the total energy.

This Nusselt number correlation was developed using spheres of steel, copper and silver. Experimental results indicate that for particles with an oxide layer on the surface and a low superheat, the Nusselt number may be **80%** higher than that for particles with a polished surface. At high superheats, the heat transfer coefficients for oxidized and polished particles converge. Although particles in a debris bed in a nuclear reactor are expected to be oxidized, they may also be very hot, so a multiplier to account for oxidized surfaces is applied.

The surface heat transfer coefficient for film boiling is then calculated by the equation

$$h_{sfb} = (Nu) \frac{k_g}{D_p} \qquad (11)$$

where

h_{sfb} = surface heat transfer coefficient for film boiling ($W/m^2 \cdot K$),

2.2.3 Transition Boiling

In the transition boiling mode of heat transfer, when the debris temperature is between T_{nuc}, and T_{TF}, the heat transfer coefficient is calculated by the equation

$$h_{str} = \frac{(T_D - T_{nuc})}{(T_{TF} - T_{nuc})} [h_{sfb} - h_{snuc}] \qquad (12)$$

where h_{str} is the heat transfer coefficient for the transition boiling mode of heat transfer, and the variable T_{TF} is the

temperature of debris at which transition boiling heat transfer ends and film boiling heat transfer begins. This temperature, T_{TF}, is given by the equation

$$T_{TF} = 0.16 \frac{\rho_g h_{fg}}{k_g} \left[\frac{g(\rho_f - \rho_g)}{(\rho_f + \rho_g)} \right]^{2/3} \left[\frac{\mu_g}{g(\rho_f + \rho_g)} \right]^{1/3} \left[\frac{\sigma}{g(\rho_f + \rho_g)} \right]^{1/2} + T_{sat}. \quad (13)$$

2.2.4 Transition from Film Boiling to Convection to Steam

The transition from the film-boiling mode of heat transfer to the convection to steam mode of heat transfer is assumed to occur when the void fraction of vapor is between α_4 and 1, where α_4 is the void fraction at which the flow regime changes from inverted slug-mist flow to mist flow. The equation for calculating α_4 is described in Reference 2. In this range of void fractions, the heat transfer to the liquid and vapor phases are calculated by the equations

$$Q_{cf} = (1 - W_{fg}) A_s h_{sfb} (T_D - T_{sat}) \quad (14)$$

$$Q_{cg} = W_{fg} Q_{conv} \quad (15)$$

where

Q_{cf} = heat transfer to liquid phase,

Q_{cg} = heat transfer to vapor phase, and

the weighting function (W_{fg}) is defined in Reference 12.

2.2.5 Total Heat Transfer to Liquid and Vapor Phases for Two-Phase Flow

The heat transfer to the liquid phase by convection is calculated by the equation

$$Q_{cf} = A_s h_{sf} (T_D - T_{sat}) \quad (16)$$

where

Q_{cf} = total heat transfer to liquid phase by convection (W/m^3),

h_{sf} = heat transfer coefficient corresponding with the applicable mode of heat transfer ($W/m^2 \cdot K$). For forced convection to liquid, units of h_{sf} are ($W/m^3 \cdot K$).

The total heat transferred to the fluid is calculated by the equation

$$Q_{tot} = Q_{cf} + Q_{rf} + Q_{cg} + Q_{rg} \quad (17)$$

where

Q_{tot} = total heat transferred to the fluid (vapor and liquid phase) (W/m^3),

Q_{rf} = total heat transfer to liquid phase by radiation,

Q_{rg} = total heat transfer to vapor phase by radiation.

If the void fraction of vapor is less than α_4, the terms for heat transfer to the vapor in the above equation are equal to zero.

The total heat transferred to the vapor phase is calculated by the equation

$$Q_{totg} = Q_{cg} + Q_{rg} \quad (18)$$

where

Q_{totg} = total heat transferred to the vapor phase (W/m^3). If the void fraction of vapor is less than α_4, this term is equal to zero.

The vapor generation is calculated by the equation

$$\Gamma_w = (Q_{cf} + Q_{rf}) / h_{fg} \quad (19)$$

where

Γ_w = volumetric vapor generation rate ($kg/m^3 s$).

3. Modeling of Debris Bed Flow Losses

The resistance applied to the flow of liquid and vapor phases of the fluid due to contact with the debris is a function of velocities and volume fractions of the liquid and vapor phases. The flow losses are calculated in terms of drag force (pressure loss gradient) in the porous debris. In the equations below, this drag force is represented by the terms $F_{\rho g}$ and $F_{\rho f}$ for the vapor and liquid phases of the fluid, respectively. These terms have the units of N/m^3. Capillary forces are assumed to be negligible.

The drag forces for the liquid and vapor phases are calculated by the equations

$$F_{pg} = \varepsilon \left[\frac{\mu_g j_g}{k \, k_{gr}} + \frac{\rho_g j_g^2}{m \, m_{gr}} \right] \quad (20)$$

$$F_{pf} = \varepsilon \left[\frac{\mu_f j_f}{k\ k_{fr}} + \frac{\rho_f j_f^{\,2}}{m\ m_{fr}} \right] \qquad (21)$$

where

F_{pg}, F_{pf} = flow resistances to the vapor and liquid phases, respectively (N/m^3),

ε = porosity of the debris,

μ_g, μ_f = viscosities of the vapor and liquid phases, respectively ($kg/m \cdot s$),

ρ_g, ρ_f = densities of the vapor and liquid phases, respectively (kg/m^3),

j_g, j_f = superficial velocities of the vapor and liquid phases respectively (m/s),

k = Darcy permeability of the debris(m^2),

k_{gr}, k_{fr} = relative permeabilities for the vapor and liquid phases, respectively,

m = passability of the debris bed (m),

m_{gr}, m_{fr} = relative passabilities for the vapor and liquid phases, respectively.

The second term on the right hand side of the above equations represents the turbulent drag counterpart to the viscous drap represented by the first term.

The Darcy permeability is calculated by the equation

$$k = \frac{\varepsilon^3 D_p^2}{150(1-\varepsilon)^2} \qquad (22)$$

where

D_p = diameter of debris particles (m).

The passability of the debris bed is calculated by the equation

$$m = \frac{\varepsilon^3 D_p}{1.75(1-\varepsilon)} \qquad (23)$$

The relative permeabilities and passabilities of the debris bed are a function of the effective saturation of the debris bed, which is calculated by the equation

$$s = \frac{s_t - s_r}{1 - s_r} \qquad (24)$$

where

s = effective saturation of debris bed,

s_t = true saturation of debris bed (volume fraction of liquid water in interstices of debris bed),

s_r = residual saturation.

The residual saturation is calculated by the equation

$$s_r = 0.0116 \left[\frac{\sigma \cos\theta}{k \rho_f g} \right]^{0.263} \qquad (25)$$

where

s_r = residual saturation,

σ = surface tension (N/m),

g = acceleration of gravity (9.8 m/s^2),

θ = wetting contact angle (radians).

The wetting contact angle is assumed to have a value of 0.785 radians.

The relative permeabilities of liquid and vapor phases are calculated by the equations[22]

$$k_{rg} = 1.0\varepsilon^{-4.43s} \qquad (26)$$

$$k_{rf} = 0.0226\varepsilon^{3.79s}. \qquad (27)$$

The relative permeabilities of the two phases as a function of effective saturation are plotted in Figure 1. The relative permeability of the vapor phase approaches a value of 1.0 as the effective saturation approaches 0.0. Similarly, the relative permeability of the liquid phase approaches 1.0 as the effective saturation approaches 1.0.

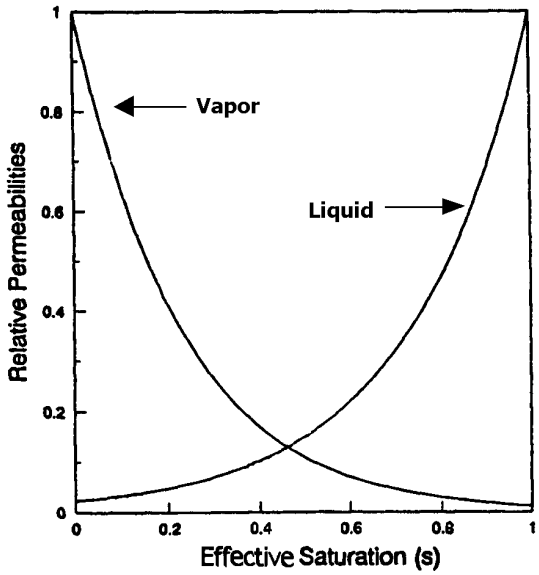

Figure 1. Relative permeabilities of the liquid and vapor phases.

The relative passabilities of the vapor and liquid phases are assumed to equal the relative permeabilities of the two phases, respectively. Numerical studies have shown that calculated results are rather insensitive to this assumption.[22]

Interfacial drag is assumed to not be significant. This assumption is applicable when the size of the debris particles is not large ($D_p < 5$ mm).[22]

The flow loss model of Tung[12] has also been implemented into SCDAP/RELAP5 and may be used as an alternative to the Chung and Catton flow loss model described above. Although the Tung model involves considerably more equations than the Chung and Catton model, calculations have shown the two models produce similar results.

4. Assessment of SCDAP/RELAP5 Debris Bed Thermal-Hydraulic Modeling

The models for thermal hydraulic behavior in porous debris were assessed by comparing the pressure drop calculated by SCDAP/RELAP5 with that calculated by benchmarked pressure drop models, and by comparing calculated and measured temperatures for the case of reflood from the bottom of an initially hot debris bed.

The assessment problems for pressure drop involved the steady state analyses of the coolant conditions in a porous debris bed with forced flow at the bottom boundary of the debris bed. A schematic of the system analyzed is shown in Figure 2.

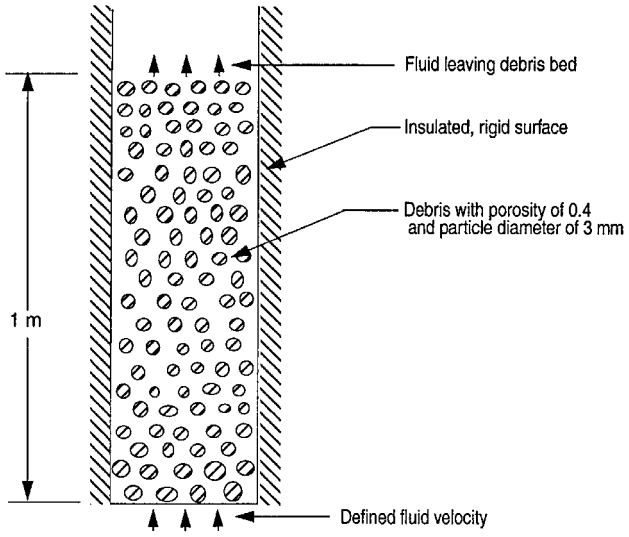

Figure 2. Schematic of debris bed analyzed for assessment of flow loss calculations.

The assessment was performed for the following cases of coolant conditions: (1) superheated steam, (2) subcooled liquid, and (3) two-phase water. The heat generation rate in the debris was zero for the first two cases, and 7.5 MW/M^3 for the two-phase case. The coolant pressure was 6.9 MPa for all three cases.

For all three cases, two boundary conditions were defined. The first boundary condition was the velocity of the fluid at the bottom of the debris bed. This velocity was 0.132 m/s for the superheated steam case, 1.39×10^{-2} for the subcooled liquid case, and 1.47×10^{-2} m/s for the two-phase case. The second boundary condition was the temperature and quality of the fluid at the bottom of the debris bed. These two parameters were defined to be 1050 K and 1.0 for the superheated steam case, 400 K and 0.0 for the subcooled liquid case, and 558 K and 0.0 for the two-phase. For each case, the debris bed was divided into ten nodes and the fluid in the debris was represented by a stack of ten RELAP5 control volumes.

The calculation of the flow losses in porous debris was assessed by comparing SCDAP/RELAP5 calculated pressure drops with independent calculations published in the literature.[12, 21] The SCDAP/RELAP5 flow losses for the three cases and those presented in the literature for the corresponding cases are compared in Table 1, which shows the SCDAP/RELAP5 calculated flow losses are in approximate agreement with the values presented in the literature.

Table 1. Comparisons of SCDAP/RELAP5 calculated flow losses with those presented in literature for corresponding cases.

Case	Pressure drop due to flow losses (Pa)	
	SCDAP/RELAP5	Literature
Superheated steam	1.03×10^3	1.14×10^3
Subcooled liquid	1.00×10^3	1.28×10^3
Two-phase water	10.6×10^3	12.6×10^3

The modeling of heat transfer in porous debris was assessed using the results of a BNL debris experiment involving the quenching from the bottom of a hot porous debris bed.[24] During this experiment, the transient temperature distribution in the debris bed was measured. Since the transient temperature distribution is a function of the flow losses in the debris bed, this experiment in an indirect manner also assessed the modeling of flow losses. A schematic of the experiment is shown in Figure 3.

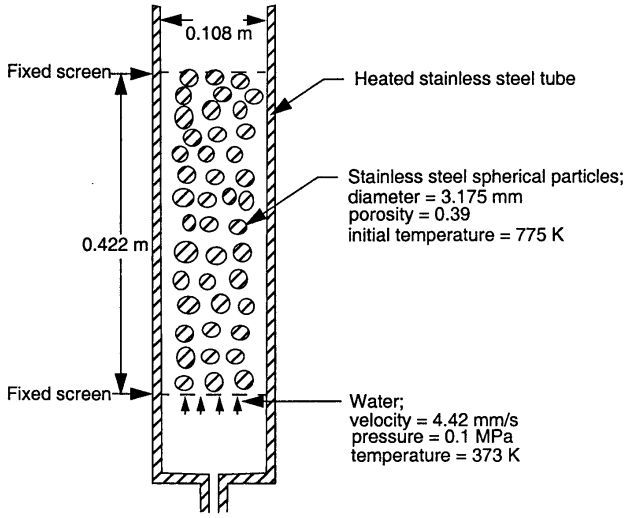

Figure 3. Schematic of BNL quenching experiment.

The calculated transient temperatures at two different elevations along the centerline of the debris bed were in general agreement with the measured transient temperatures. The calculated and measured transient temperatures for the two elevations are compared in Figure 4. The elevation of 0.025 m is near the bottom of the debris bed, where reflood began, and the elevation of 0.24 is slightly above the midplane of the debris bed. The overprediction of the temperature at the 0.24 m elevation in the period from 40 s to 50 s is considered due to two-dimensional hydrodynamic behavior, wherein the liquid phase moved up along the wall, formed a pool at the top, and then some of the water flowed down the center region of the debris bed.[24] Nevertheless, the calculated and measured trend in quenching are in good agreement.

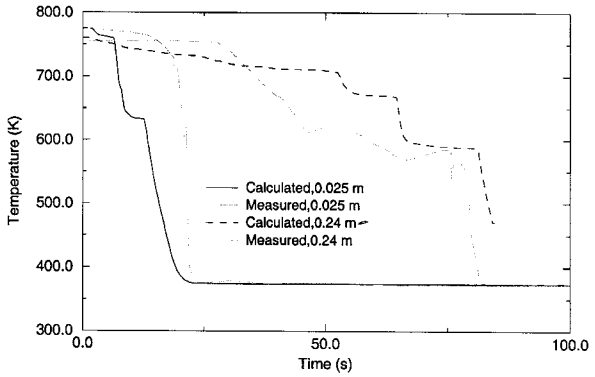

Figure 4. Comparison of calculated and measured transient temperature distribution in debris bed.

In conclusion, the assessment indicates that SCDAP/RELAP5/MOD3.3 is correctly modeling the flow losses and heat transfer in porous debris. The SCDAP/RELAP5 calculated flow losses for three different conditions of coolant were similar to those presented in the literature for corresponding conditions. The SCDAP/RELAP5 calculated transient temperature distribution in a hot debris bed reflooded from the bottom was similar to the measured transient temperature distribution.

6. Conclusions

This paper described the methodology used in SCDAP/RELAP5/MOD3.3 for calculating the heat transfer and flow losses in porous debris located either in the core region or in the lower head of a reactor vessel. An earlier code version calculated convective and radiative heat transfer from the surfaces of nonporous debris in a detailed manner but model only in a simplistic manner the heat transfer and flow losses in porous debris. In order to advance beyond this simplistic modeling, designs were developed for a detailed calculation of heat transfer and flow losses in porous debris and for an accounting of the heat transfer and flow losses in the field equations of the RELAP5 part of the code.

For the modeling of heat transfer, six modes of convective heat transfer were distinguished and correlations defined for each mode. The six modes of heat transfer were; (1) forced convection to liquid, (2) forced convection to gas, (3) nucleate boiling, (4) transition boiling, (5) film boiling, and (6) transition from film boiling to convection to vapor. The boundaries between the modes of heat transfer were defined as a function of the volume fraction of vapor and the debris temperature. In general, the correlations calculate the rate of convective heat transfer as a function of the local fluid conditions and the local debris porosity, particle size, and temperature.

A model based on Darcy's Law was implemented into the SCDAP/RELAP5 code to calculate the flow losses of the liquid and vapor phases of water in porous debris. The relative permeabilities and passabilities of the two phases are calculated as a function of the effective saturation of the debris bed. Viscous and turbulent drag are represented by the model.

The models for thermal hydraulic behavior in porous debris were assessed by comparisons of SCDAP/RELAP5 calculated behavior of debris with that evaluated by measurements and other benchmarked models presented in the literature. The models for flow loss were assessed by comparing the pressure drop calculated by SCDAP/RELAP5 with that calculated by benchmarked pressure drop model. These comparisons indicated that the code is correctly calculating the flow losses for fluid conditions ranging from single phase vapor to liquid or two-phase fluid. The models for heat transfer were assessed by comparing calculated and measured temperatures for the case of reflood from the bottom of an initially hot debris bed. These comparisons showed that the calculated transient temperature distribution was in generally good agreement with the measured transient temperature distribution.

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