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A BEST ESTIMATE RADIATION HEAT TRANSFER MODEL DEVELOPED FOR TRAC-BD1

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NOMENCLATURE

A_k	heat transfer area for kth surface
$a_{\ell kj}$	absorptivity of the droplet phase along path k to j
a_{vkj}	absorptivity of the vapor phase along path k to j
B_k	radiosity for surface k
D_d	average droplet diameter
d	droplet subscript
F_{kj}	view factor from surface k to surface j
H_k	incident radiation heat flux to surface k
K	spectral absorption coefficient
K_{Dkj}	absorption coefficient for the droplet phase along path k to j
ℓ	liquid phase subscript
L_{kj}	path length from surface k to j
N	total number of radiating heat transfer surfaces
P	pressure
T_k	surface temperature for the kth surface
T_ℓ	liquid temperature
T_v	vapor temperature
v	vapor phase subscript
α	volume fraction
σ	Stefan-Boltzmann constant
ϵ_k	emissivity of surface k
ϵ_{kj}	emissivity of the droplet phase along path k to j
ϵ_{vkj}	emissivity of the vapor phase along path k to j
δ_{kj}	Kronecker Delta
τ_{kj}	transmissivity of the two-phase mixture along path k to j
$\tau_{\ell kj}$	transmissivity of the liquid phase along path k to j

τ_{vkj} transmissivity of the vapor phase along path k to j

μ_{ij} anisotropic reflection factor

ω wave number (reciprocal wave length)

ABSTRACT

A best estimate radiation heat transfer model for analysis of BWR fuel bundles has been developed and compared with 8x8 fuel bundle data. The model includes surface-to-surface and surface-to-two-phase fluid radiation heat transfer. A simple method of correcting for anisotropic reflection effects has been included in the model.

INTRODUCTION

A best estimate radiation heat transfer model has been developed and implemented into the fuel bundle component model for the BWR (Boiling Water Reactor) version of the TRAC (Transient Reactor Analysis Code) computer code being developed at the INEL (Idaho National Engineering Laboratory).[1] The TRAC[2] computer code was originally developed at the Los Alamos Scientific Laboratory for LOCA (Loss of Coolant Accident) analysis of a pressurized water reactor. The TRAC-BD1 code being developed at INEL for the Nuclear Regulatory Commission has the basic capability for modeling of BWR LOCA's.

During the refill portion of a BWR-LOCA, radiation heat transfer from the rods to the channel box walls can be the predominant mode of heat transfer. The TRAC-BD1 radiation heat transfer model includes radiative heat transfer from surface-to-surface as well as from surfaces to the nonequilibrium two-phase mixture. The liquid phase is treated as a gray fluid, however, the nongray behavior of the vapor phase is represented by approximating the integral of the water vapor absorption bands weighted by the Planck black body radiation distribution. A method for quickly performing the integration of emissivity over absorption bands has been developed. To first order, the surfaces are treated as gray and diffuse. An anisotropic reflection correction factor has been included to approximate higher order reflection effects.

MODEL DESCRIPTION

Assuming that the rods are diffuse gray surfaces with no azimuthal surface temperature variation, the surface-to-surface radiation exchange is described by the conservation of radiated energy for surface k, as expressed by Equation (1).

$$A_k B_k = \varepsilon_k \sigma T_k^4 + (1 - \varepsilon_k) H_k \tag{1}$$

The total heat flux incident on surface k from all other surfaces, liquid regions, and vapor regions is obtained from the following equation:

$$A_k H_k = \sum_{j=1}^{N} \{ B_j \tau_{jk} + \varepsilon_{vjk} \tau_{\ell jk} \sigma T_v^4 + \varepsilon_{\ell jk} \tau_{vjk} \sigma T_\ell^4 \} A_j F_{jk} \tag{2}$$

In Equation (2) it has been implicitly assumed that vapor and liquid phases are dispersed, of uniform temperature and gray. It is also assumed that the view factor from surface j to the liquid and vapor phases lying in the path between surfaces j and k is given by F_{jk}. Liquid and vapor transmissivities are given by $\tau_{ij} = 1 - a_{ij}$.

Equations (1) and (2) can be combined to yield an equation for surface k involving the radiosities of all surfaces.

$$\sum_{j=1}^{N} [\delta_{jk} - (1 - \varepsilon_k) \tau_{jk} F_{kj}] B_j = \varepsilon_k \sigma T_k^4 + (1 - \varepsilon_k) \sum_{j=1}^{N} [\varepsilon_{vjk} \tau_{\ell jk} \sigma T_v^4 + \varepsilon_{\ell jk} \tau_{vjk} \sigma T_\ell^4 \quad F_{kj} \tag{3}$$

An equation of this form can be written for each surface (k = 1,N) yielding N linear equations and N unknown radiosities. This set of equations can then be solved for the radiosities in terms of the other quantities in Equation (3). The radiative heat flux leaving surface k then can be calculated from Equation (4).

$$q_k = B_k - H_k = \frac{\varepsilon_k (\sigma T_k^4 - B_k)}{1 - \varepsilon_k} \tag{4}$$

The surface and fluid temperatures from the previous time step are used to evaluate Equations (3) and (4). View factors are calculated by the code assuming fuel rod bundle geometry and employing the crossed-string method[3] to obtain rod-to-rod view factors. The conservation of radiant energy is used to obtain the rod-to-channel wall view factor. The reciprocity relationship, $A_jF_{jk} = A_kF_{kj}$, is used to calculate the channel-to-rod view factors. The equivalent flat plate method[4] is used for the calculation of mean beam lengths between individual surfaces.

Liquid and vapor absorptivities and emissivities are calculated assuming that the radiation heat transfer model will be applied only in the drop-annular flow regime. The absorptivity of droplets has been estimated in Reference [5] by applying the optically thin assumption to obtain Equation (5).

$$a_{kj} = 1 - e^{-K_{Dkj} L_{kj}} \qquad (5)$$

Reference [5] has estimated the absorption coefficient for droplets to be

$$K_{Dkj} = \frac{1.11\ \alpha_d}{D_d} \qquad (6)$$

If the droplets are assumed to be gray, their emissivity is equal to the absorptivity given by Equation (5).

The emissivity of steam is calculated taking account of the absorption and emission spectrum of water vapor. The emissivity of an absorbing gaesous medium for monochromatic radiation of wave number ω is given by Equation (7)

$$\varepsilon(\omega) = 1 - e^{-K(\omega)PL} \qquad (7)$$

The total emissivity, ε, of the medium is obtained by integrating Equation (7) over all wave numbers, with the Planck black body radiation distribution as a weighting function, Thus,

$$\varepsilon = \frac{\int_0^\infty \varepsilon(\omega)\, B(\omega,T)\, d\omega}{\int_0^\infty B(\omega,T)\, d\omega} = \frac{\int_0^\infty \varepsilon(\omega)\, B(\omega,T)\, d\omega}{\sigma T^4} \qquad (8)$$

where the Planck function $B(\omega,T)$ is given by

$$B(\omega,T) = \frac{2\pi hc^2\omega^2}{e^{hc\omega/kT} - 1}$$

The absorptivity α, of the medium may be obtained by evaluating Equation (8) at the temperature T_s of the surface emitting the radiation incident on the absorbing medium, or

$$\alpha = \frac{\int_0^\infty \alpha(\omega)\, B(\omega,T_s)\, d\omega}{\sigma T_s^4} \qquad (9)$$

where by Kirchoff's law, $\alpha(\omega) = \varepsilon(\omega)$ in thermodynamic equilibrium.

The absorption spectrum of water vapor is generally considered to consist of six major absorption bands. The wave numbers and absorption coefficients associated with these bands are given in Reference [6] and are shown in Table 1. The values given in this table were obtained for the Thomson model of emissivity. The absorption coefficient values given in Table 1 were obtained for a reference temperature of 300 K. As discussed in Reference [6], these values are assumed to vary inversely with water vapor temperature to account for various line broadening phenomena, or

$$K(\omega) = K_o(\omega)\ \left(\frac{T_o}{T}\right)$$

where T_o = 300 K and $K_o(\omega)$ is the tabular value of K_ω. The values of $K(\omega)$ used in the present model are assumed to be constant within each band, and zero in the region between bands.

TABLE 1. WATER VAPOR ABSORPTION BAND DATA

Wave Length of Band Center (μ)	Minimum Wave No. (cm^{-1})	Maximum Wave No. (cm^{-1})	Absorption Coefficient $k_o(w)$ (Atm^{-1} cm^{-1})
20.0	195.5	804.5	0.0959
6.3	1283.0	1892.0	0.2874
2.7	3399.0	4008.0	0.2069
1.87	5043.0	5652.0	0.0166
1.38	6942.0	7551.0	0.0136
1.1	8468.0	9077.0	0.00053

Using the data in Table 1, the integrals in Equations (8) and (9) can be approximately evaluated as sums over bands as follows:

$$\varepsilon = \sum_{i=1}^{6} \frac{\varepsilon(\omega_i)\ \overline{B(\omega_i T)}\ \Delta\omega_i}{\sigma T^4} \qquad (10)$$

$$\alpha = \frac{\sum_{i=1}^{6} \varepsilon(\omega_i)\ \overline{B(\omega_i T_s)}\ \Delta\omega_i}{\sigma T_s^{\ 4}} \qquad (11)$$

where i is the band index, and $\overline{B(\omega_i,T)}$ is the average value of the Planck black body function over bank i. In the Thomson model, this value is obtained by integrating $B(\omega,T)$ over the entire band, while in the present model, it is obtained by evaluating $B(\omega,T)$ at the mean wave number $\bar{\omega}_i$ of the band, or

$$\overline{B(\omega_i,T)} = B(\bar{\omega}_i,T) \qquad (12)$$

Equations (10) and (12) are compared with Thomson's model in Figure 1. From Figure 1 it is apparent that the TRAC-BD1 method for ε_v is quite accurate for PL < .1 MPa-m and T_v > 1111 K which bounds the conditions that would be

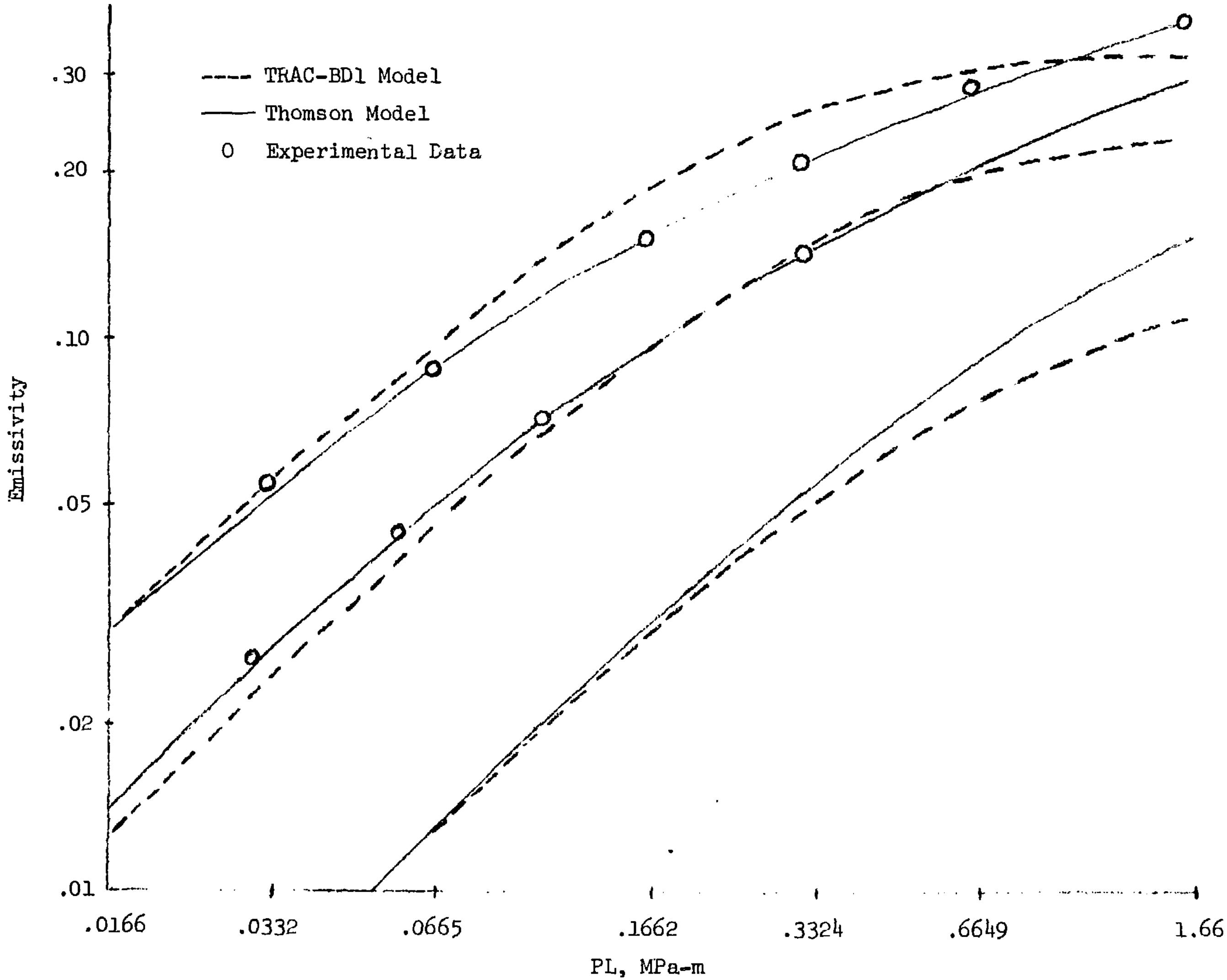

Figure 1. Water vapor emissivity.

anticipated in a BWR bundle when radiation heat transfer is important. At longer path lengths the two methods diverge, however, these path lengths are not possible in a BWR fuel bundle.

For the analyses performed in this paper, two different methods were used for treating radiation reflection between surfaces. The first of these methods, isotropic reflection, simply assumes that the radiation reflected from a surface, hence, the radiosity of that surface is uniform in all directions. This assumption is justified in regions where neighboring surfaces in all directions have nearly the same temperature. However, in regions where neighboring surface temperatures differ greatly from one side of a given surface to another this assumption is not valid. An example of this would be a fuel rod near the corner of the fuel bundle and adjacent to the relatively cool channel wall. In this case we would not expect the radiosity to be the same in all directions.

To account for the effect of nonuniform radiosity, a second method of treating reflection has been added to the code. This method, anisotropic reflection, is based on the concept of an anisotropic reflection factor μ as suggested by Andersen[7]. In this method, a fraction μ_i of the radiation incident on rod i from rod j is directly reflected back to rod j, and a fraction $(1 - \mu_i)$ is reflected isotropically. This has the effect of reducing the effective view factor from rod j to rod i, and increasing the effective view factor from rod j to itself, since a fraction μ_i of all radiation sent from rod j to rod i is immediately returned.

Thus, in TRAC-BD1 the anisotropic factor μ_i is used to modify the view factors used in Equations (1) through (4) in accordance with Equations (13) and (14).

$$F'_{ij} = F_{ij} (1 - \mu_{ij}) \qquad \text{for } i = j \qquad (13)$$

$$F'_{ii} = F_{ii} + \sum_{j=1}^{N} F_{ij} \mu_{ij}. \qquad (14)$$

These new effective view factors conserve radiant energy and satisfy the reciprocity relationship if $\mu_{ij} = \mu_{ji}$. In accordance with the recommendations of Tien et al[8], a value of 0.5 is used for μ_{ij} for rod-to-rod radiation and 0.15 for channel wall-to-rod radiation.

COMPARISON TO TEST DATA

The TRAC-BD1 radiation model has been compared to 64 rod bundle data obtained in the Göta[9] test loop. Radiation test data was obtained by setting the bundle power to a constant value with stagnant steam at atmospheric pressure inside the channel box (rod bundle housing). Running water on the channel box outside walls maintained the wall at saturation temperature. The rod and box temperatures were recorded when they reached a steady state value. During steady state all the rod power is being absorbed by the channel box with radiation being the dominant heat transfer mode.

The rods at the bundle axial midplane were modeled using the TRAC-BD1 code. The calculated temperatures of the rods along a diagonal line are compared to the measured temperatures in Figure 2. When the calculation was performed assuming isotropic (uniform) rod-to-rod reflection, the rod-to-rod temperature difference was underpredicted. The center temperatures were underpredicted by up to 100 K.

Although the surface emissivity values used were obtained from Reference [9], a possible explanation of the temperature gradient error is that the surface emissivity values used in the calculation were incorrect. However, adjustment of emissivity values only resulted in raising or lowering of the entire temperature distribution in the bundle. Uniform adjustment of surface emissivities did not significantly change the temperature gradient from the center of the bundle to the outer edge. The isotropic calculation shows approximately a 150 K temperature difference from the center rods to the peripheral rods, whereas, the data shows about a 250 K temperature difference.

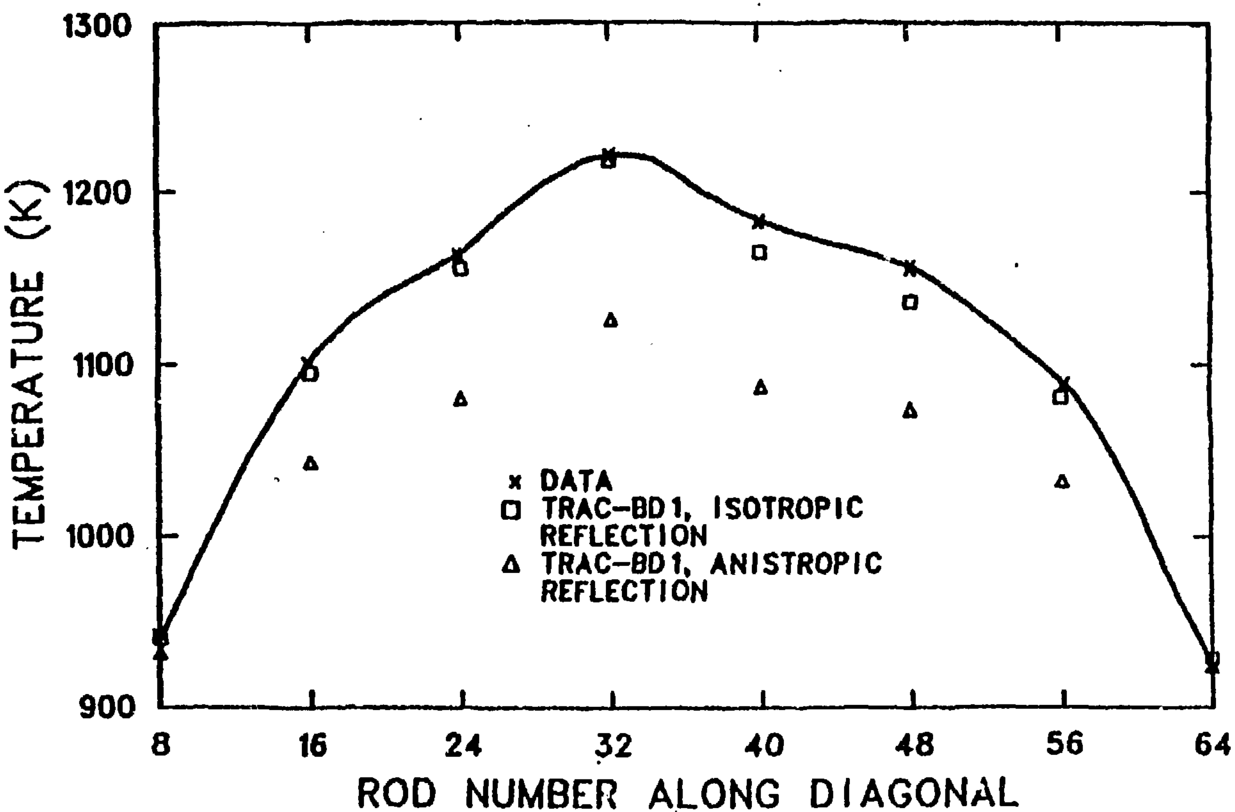

Figure 2. Göta radiation test 27 vs. TRAC-BD1.

Another possible explanation for the error is that the steam temperature variation radially across the bundle results in the larger temperature difference in the test as compared to the calculation, since the calculation considers a uniform steam temperature. However, forcing the code to use a steam temperature profile similar to the rod profile did not increase the calculated temperature difference from bundle center rod to peripheral rods. Others[7,8] have observed the same behavior in rod bundles when attempting to use isotropic calculations to compare to data.

The TRAC calculation was repeated with the anisotropic reflection view factor correction described previously. The results of this calculation are also shown in Figure 2. The comparison with data is greatly improved. The additional computer time required using anisotropic reflection is negligible since the anisotropic factor only enters the calculation during the initial calculation of view factors.

CONCLUSIONS

The TRAC-BD1 radiation heat transfer model has been used to accurately calculate steady state conditions in the steam filled Göta test facility. Though the test case presented gives no indication of the ability of the radiation model to treat two-phase conditions, it does provide an excellent verification of the effective performance of the anisotropic radiation correction. Though an exact treatment of anisotropic radiation effects would be much more complicated than the method presented in this paper, it is concluded that a simple modification of view factors yields accurate results.

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