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TECHNICAL NOTES

INTERACTION OF CONVECTION AND RADIATION HEAT TRANSFER IN HIGH PRESSURE AND TEMPERATURE STEAM

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NOMENCLATURE

- A_a^* isothermal band absorptance
- c_p specific heat at constant pressure
- $I_{b\omega}$ Planck's blackbody function
- $I'_{b\omega_i}$ function defined as $dI_{b\omega_i}(\eta)/d\eta$
- k effective (molecular plus turbulent) thermal conductivity
- Nu local Nusselt number, $2Rh/k$
- q heat flux
- Pr Prandtl number
- R tube radius
- Re Reynolds number
- r radial coordinate
- r^* dimensionless radius, r/R
- T temperature
- x axial coordinate.

Greek symbols
- α_i integrated band intensity
- ρ density
- τ_R optical depth of the tube radius at maximum absorption, $\alpha\rho R/\omega$
- ω wave number.

Subscripts
- c convection
- i ith band
- 0 absence of interaction between convection and radiation
- r radiation or radial
- w wall.

INTRODUCTION

COMBINED convection and radiation heat transfer from infrared radiating gases flowing in circular tubes was examined for laminar and turbulent flow at relatively small system pressure–dimension products [1–4], and the interaction between convection and radiation was found to be only moderate. However, under the conditions experienced by the Three Mile Island nuclear reactor [5], the steam flow rates through the core were quite low and pressures as well as the temperatures were high. For these types of conditions the interaction between convection and radiation is expected to be much more significant. The need to realistically predict heat transfer under simulated accident conditions has provided the motivation for this work. It was considered desirable to estimate what order of magnitude errors would be introduced in the convective heat transfer coefficient calculations by the neglect of the interaction between convection and radiation. To this end, a simple model was considered.

ANALYSIS

Physical model and basic equations

Steady, fully developed laminar flow and heat transfer in a tube were considered since the interaction between convection and radiation is expected to be greater than for turbulent flow. It was assumed that at $x > 0$, there is a step change in the surface temperature or in the heat flux at the tube wall. Heat conduction and radiation transfer in the flow direction were assumed to be negligible in comparison with that in the radial direction. The validity of this assumption depends on the axial temperature gradient, the conduction–radiation parameter, and the tube geometry. For nuclear reactor fuel assemblies where the expected gradients and rod spacings are small, the axial component is negligible in comparison with the radial one [2]. The tube wall was assumed to be black, and pure steam was taken to be the coolant. Viscous heat dissipation was neglected. Buoyancy effects were ignored, but the physical property variations of steam with temperature were accounted for.

Based on the above idealizations, the energy equation governing the temperature distribution in steam reduces to [1, 6]

$$\rho c_p u(r)\frac{\partial T}{\partial x} = \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(k\frac{\partial T}{\partial r} - q_{rr}\right)\right], \qquad (1)$$

where the velocity distribution $u(r)$ is assumed to be Poiseuillean. The inlet and boundary conditions are assumed to be

$$T = T_0 \quad \text{for} \quad x \leqslant 0 \quad \text{and any} \quad r, \qquad (2)$$

$$\partial T/\partial r = 0 \quad \text{at} \quad r = 0, \qquad (3)$$

$$T = T_w \quad \text{or} \quad -k\,\partial T/\partial r = q_w \quad \text{at} \quad r = r_0. \qquad (4)$$

The radiation transfer to water vapor in a cylindrical tube must account for the cylindrical geometry and the nature of the selective absorption of radiation by steam. The exponential wide band model [3] was used to account for banded radiation (five bands). The total radiative flux in the radial direction q_{rr} can be expressed as

$$q_{rr}(r) = \int_0^\infty q_{rr,\omega}(r)\,d\omega \approx \sum_{i=1}^{5}\int_{\Delta\omega_i} q_{rr,\omega_i}\,d\omega_i = \sum_{i=1}^{5} q_{rr,i}, \qquad (5)$$

where $q_{rr,i}$ is the radiative flux for band i and ω denotes the wave number. For a black tube wall, assuming that the bands are sufficiently narrow so the Planck blackbody intensity of radiation, $I_{b\omega}$, does not vary sufficiently over a band, the radiative flux for the ith band becomes [6]

$$q_{rr,i}(r^*) = \omega_i \int_{\gamma=0}^{\pi/2} \cos\gamma \left[\int_{r^*}^{1} I'_{b\omega_i}(\eta) A^*_{a,i}(x_{i,+1})\, d\eta - \int_{r^* \sin\gamma}^{1} I'_{b\omega_i}(\eta) A^*_{a,i}(x'_{i,-1})\, d\eta + \int_{r^* \sin\gamma}^{r^*} I'_{b\omega_i}(\eta) A^*_{a,i}(-x'_{i,+1})\, d\eta \right] d\gamma \quad (6)$$

where

$$x'_{i,j} = \tau_{R,i} |(\eta^2 - r^{*2} \sin^2\gamma)^{1/2} - jr^* \cos\gamma|. \quad (7)$$

The axial band absorptance $A^*_{a,i}$ of band i was calculated from the correlations given in ref. [6].

The water spectrum is composed of five bands [3, 7]. Each band is characterized by three parameters: (1) the integrated band intensity α_i, (2) the exponential decay width ω_i, and (3) the mean line width: spacing ratio β_i. The equivalent line width model for the width: line ratio β_i and the exponential wide band model parameters published in ref. [3] were used in the calculations. The integrated band intensity and the exponential band width were calculated for the specified temperature and the partial (total) pressure.

Various approaches have been proposed to incorporate nonhomogeneous effects into a homogeneous description for the band absorptance [3, 7]. However, owing to the uncertainty in the band parameters for steam at thermal conditions of interest (i.e. high pressure 68 atm) and high temperatures (700 K $\leqslant T \leqslant$ 2000 K) and to that fact that the original band correlations have an RMS error of about 13%, the scaling did not appear to be warranted, and a constant property prediction was used instead.

Method of solution

If the divergence of the radiative flux in equation (1) is denoted by S, the energy equation can be considered to be a parabolic partial differential equation with a source (sink) which is a function of both the axial and the radial position. The thermophysical properties of steam were evaluated at the film temperature. The energy equation was solved numerically by using an explicit, central differencing scheme [8] and the finite-difference approximation of equation (1), which can be expressed as

$$T_j^{n+1} = T_j^n + \left|\frac{k}{\rho c_p u r}\right|_j \left|\frac{\Delta x}{2\Delta r}\right| [T_{j+1}^n - T_{j-1}^n] + \left|\frac{k}{\rho c_p u}\right|_j \left|\frac{\Delta x}{\Delta r^2}\right| [T_{j+1}^n - 2T_j^n + T_{j-1}^n] + \left|\frac{S\Delta x}{\rho c_p u}\right|_j. \quad (8)$$

At the center of the tube, equation (8) specializes to

$$T_1^{n+1} = T_1^n + 2\left|\frac{k}{\rho c_p u}\right|_1 \left|\frac{\Delta x}{\Delta r^2}\right| [T_2^n - T_1^n]. \quad (9)$$

If all temperatures T_j^n are known at position $n\Delta x$, equations (8) and (9) enable T_j^{n+1} to be calculated directly at the axial position $(n+1)\Delta x$ for $1 \leqslant j \leqslant N_{max} - 1$. For this purpose, we had to know the source $S(x, r) = S_j^n$ at each radial node j and axial node n. The radiative flux in the radial direction q_{rr}, defined by equation (6), was calculated by double integration in the radial direction r and angle γ to find q_{rr_i} for each band and then was summed over all the bands. It should be noted that the limits of integration in equation (6) are functions of the radial coordinate r and the angle γ. The multiple integrations with variable limits were carried out using the method described in the literature [8]. The validity and accuracy of the algorithm in the absence of radiation transfer for the isothermal wall and constant property case were checked against published results for the local Nusselt number [9] and good agreement was obtained.

NUMERICAL RESULTS AND DISCUSSION

For illustration, results were obtained for high pressure (60 atm) steam in an isothermal wall (T_w = const.) tube.

A comparison of temperature distributions in the tube calculated in both the absence and presence of the interaction between convection and radiation is given in Figs. 1 and 2. The results show that when the fluid is capable of absorbing and emitting radiation, the temperature gradients at the tube wall are decreased. Hence, the convective heat flux at the tube wall is expected to be lower than when heat transfer is by convection alone. Examination of Figs. 1 and 2 reveals that the differences between the temperature profiles and between the

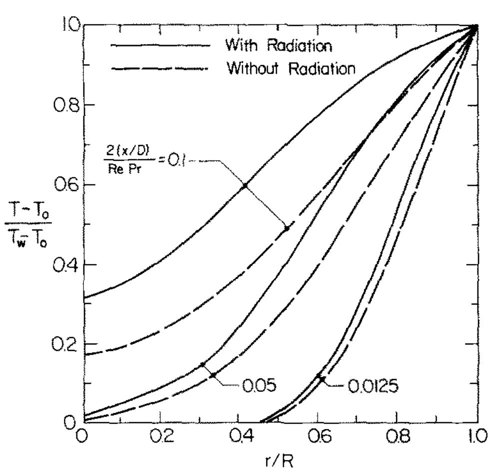

FIG. 1. Comparison of temperature distributions for laminar flow of steam in a constant wall tube calculated by neglecting and by accounting for interaction between convection and radiation: $D = 0.02$ m, $P = 68$ atm, $Re = 200$, $T_w = 1000$ K, $T_0 = 557$ K.

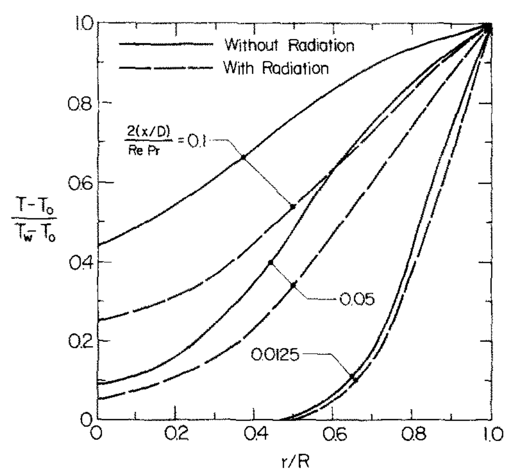

FIG. 2. Comparison of temperature distributions for laminar flow of steam in a constant wall tube calculated by neglecting and by accounting for interaction between convection and radiation: $D = 0.02$ m, $P = 68$ atm, $Re = 2000$, $T_w = 1000$, and $T_0 = 557$ K.

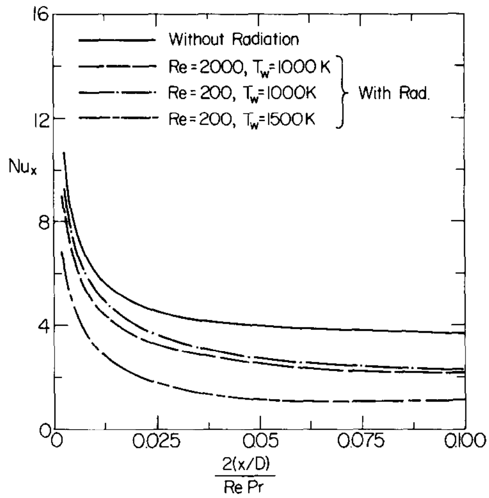

FIG. 3. Local Nusselt number variation along a constant wall temperature tube.

Table 1. Heat transfer results for combined convection and radiation in a black wall isothermal tube: $D = 0.02$ m, $P = 68$ atm, $T_0 = 557$ K

	(a) $Re = 200$, $T_w = 1000$ K				
$2(x/D)Re\ Pr$	0.0125	0.025	0.050	0.075	0.100
$q_c/q_{c,0}$	0.784	0.695	0.576	0.478	0.395
$q_r/q_{c,0}$	1.267	1.130	0.956	0.793	0.650
$Nu_x/Nu_{x,0}$	0.783	0.725	0.658	0.622	0.600
$N_{x,0}$	6.145	5.012	4.221	3.905	3.746
	(b) $Re = 200$, $T_w = 1500$ K				
$2(x/D)/Re\ Pr$	0.0125	0.025	0.050	0.075	0.100
$q_c/q_{c,0}$	0.395	0.294	0.144	0.104	0.073
$q_r/q_{c,0}$	4.473	2.940	2.837	1.997	1.436
$Nu_x/Nu_{x,0}$	0.438	0.367	0.275	0.278	0.314
$N_{x,0}$	6.200	5.001	4.128	3.883	3.757
	(c) $Re = 2000$, $T_w = 1000$ K				
$2(x/D)/Re\ Pr$	0.0125	0.025	0.050	0.075	0.100
$q_c/q_{c,0}$	0.786	0.699	0.562	0.407	0.244
$q_r/q_{c,0}$	1.214	1.069	0.855	0.673	0.406
$Nu_x/Nu_{x,0}$	0.785	0.729	0.664	0.632	0.610
$N_{x,0}$	5.610	4.510	3.998	3.821	3.711

temperature gradients increase with the distance from the tube inlet. This is due to the fact that as the temperature of the steam increases along the tube, radiation heat transfer becomes a larger fraction of the total heat transfer at the tube wall.

The local Nusselt numbers computed are illustrated graphically in Fig. 3 and are also given in Table 1 in abbreviated form, together with the ratios of the local heat fluxes. In the table, the subscript '0' denotes the results for pure convection only; the subscripts c and r denote convection and radiation, respectively.

The results of Tables 1(a) and (c) show that for a given wall temperature ($T_w = 1000$ K), the heat transfer results are not sensitive to the Reynolds number. The small differences between the results for the two cases can be explained by the dependence of the thermophysical properties on temperature. The convective heat flux ratio $q_c/q_{c,0}$ and the Nusselt number ratio $Nu_x/Nu_{x,0}$ show that the interaction between convection and radiation significantly reduces the convective heat flux and the Nusselt number. For example, the results listed in Table 1(a) show that for Graetz numbers [$Gz = 2(x/D)/Re\ Pr$] of 0.0125 and 0.1, the Nusselt number ratios are 0.783 and 0.600, respectively. This corresponds to a 22 and a 40% reduction in the convective heat transfer coefficient. The reduction becomes larger as the wall temperature is increased from 1000 to 1500 K [Table 1(b)]. In addition, the results of the table show that at higher temperatures, the local radiative flux at the wall is significantly higher than the convective flux in the absence of the interaction. Accompanying this, there is a reduction in the convective flux.

CONCLUSIONS

The results show that at low velocities, the interaction between convection and radiation heat transfer in high pressure–high temperature steam is large. Neglect of this interaction can lead one to greatly overpredict convective heat transfer at the wall. The results reported here should be evaluated considering the fact that the band parameters for high pressure–high temperature steam have not been established experimentally and are based on extrapolations [3, 7].

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