TURBULENCE-RADIATION INTERACTIONS IN NONREACTIVE FLOW OF COMBUSTION GASES

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Nomenclature

B	width of bluff body (Fig. 1)
D	width of central injection duct (Fig. 1)
I_η	spectral radiative intensity
$I_{b\eta}$	Planck function
s	position
$\hat{s}$	unit vector along a line of sight
T	temperature
Y_α	mass-fraction of α-th species

Greek

η	wave number
κ_η	spectral absorption coefficient

INTRODUCTION

A nonreactive hot mixture of radiatively participating species, typically carbon dioxide and water vapor, may be found in the exhaust sections of almost all combustors. Since the scalar fluctuations in such nonreactive flows are substantially smaller than in flames, it is commonly believed that the effects of turbulence-radiation interactions (TRI) on altering wall heat fluxes in nonreactive flows are negligible. Such belief, however, has not been substantiated by evidence to date. The purpose of this note is to investigate the conditions under which turbulence-radiation interactions may be important in nonreactive flows. The final outcome was found to be largely dependent on how the scalar fluctuations correlate, rather than the magnitude of the fluctuations themselves. It was found that for most situations of practical interest, TRI effects are indeed negligible.

THEORY

The absorption coefficient of a mixture of gases is a function of its temperature and composition (Modest, 1993). In a turbulent flow, the fluctuations in the scalar field cause the absorption coefficient to fluctuate, as well. These fluctuations may correlate with the fluctuations in the Planck function (which is a function of temperature) to result in so-called turbulence-radiation interactions.

The spectral radiative transfer equation for an absorbing-emitting medium is (Modest, 1993):

$$\frac{\partial I_\eta}{\partial s} = \kappa_\eta \left(I_{b\eta} - I_\eta \right) \tag{1}$$

where I_η is the spectral radiative intensity, $I_{b\eta}$ is the Planck function, κ_η is the spectral absorption coefficient, and η is the wave number. Scattering is dominant when large soot agglomerates are present. Soot, however, is locally produced and destroyed within the flame itself, and hardly any soot is liable to be present in the exhaust section of a well-designed combustor and, therefore, scattering may be considered negligible.

Decomposition of I_η, $I_{b\eta}$, and κ_η into their mean and fluctuating parts, substitution into equation (1), and averaging, results in

$$\frac{\partial \langle I_\eta \rangle}{\partial s} = \langle \kappa_\eta \rangle \langle I_{b\eta} \rangle - \langle \kappa_\eta \rangle \langle I_\eta \rangle + \langle \kappa'_\eta \, I'_{b\eta} \rangle - \langle \kappa'_\eta \, I'_\eta \rangle \, , \tag{2}$$

where quantities within angled brackets represent averages, and quantities with primes denote fluctuations. The last two terms in equation (2) are a result of turbulence-radiation interactions. The correlation, $\langle \kappa'_\eta \, I'_\eta \rangle$, is generally negligible since the fluctuations in the absorption coefficient and the spectral radiative intensity act at completely different scales, except in an optically thick medium. Arguments to this effect have been provided in the past by Kabashnikov and coworkers (1985,1985), and by Song and Viskanta (1987).

In this work, the unknown correlation $\langle \kappa'_\eta \, I'_{b\eta} \rangle$, required for closure of the radiative transfer equation, was modeled using the velocity-composition joint probability density function (PDF) approach (Pope, 1985). Detailed descriptions on the modeling and solution procedure can be found in Mazumder (1997) and in Mazumder and Modest (1997).

Performing Taylor series expansions of κ_η and $I_{b\eta}$ about their mean values, it can be shown that, in general,

$$\langle \kappa'_\eta \, I'_{b\eta} \rangle = f \left(\langle T'^2 \rangle, \, \langle \underline{Y}' \, T' \rangle, \, \text{higher order terms} \right) \, , \tag{3}$$

where $\underline{Y}$ is a set consisting of all the species mass-fractions. Of the two second-order correlations appearing in equation (3), the correlation $\langle \underline{Y}' \, T' \rangle$ is responsible for determining whether κ_η and $I_{b\eta}$ is positive or negative, since $\langle T'^2 \rangle$ is always positive. If $\langle \kappa'_\eta \, I'_{b\eta} \rangle$ is positive, the intensity of radiation along a line of sight will be enhanced [cf. equation (2)], and if $\langle \kappa'_\eta \, I'_{b\eta} \rangle$ is negative, the intensity will be attenuated. In other words, the role of TRI essentially reduces to how the concentration fluctuations correlate with the temperature fluctuations in the medium. In flames, this correlation is always positive because local production of CO_2 or H_2O is always accompanied by production of heat (or an increase in local temperature). For nonreactive flows, this is not the case, and the matter requires further investigation.

SAMPLE CALCULATIONS

The geometry used for the sample calculations is shown in Fig. 1, and is two-dimensional planar. A mixture of carbon dioxide and water vapor (equal by mass) was injected along the centerline, as shown, at a temperature of 1000K and a velocity of 16.41 m/s. The coflowing air has a temperature of 1200K and a velocity of 10 m/s. The Reynolds number based on the inlet air

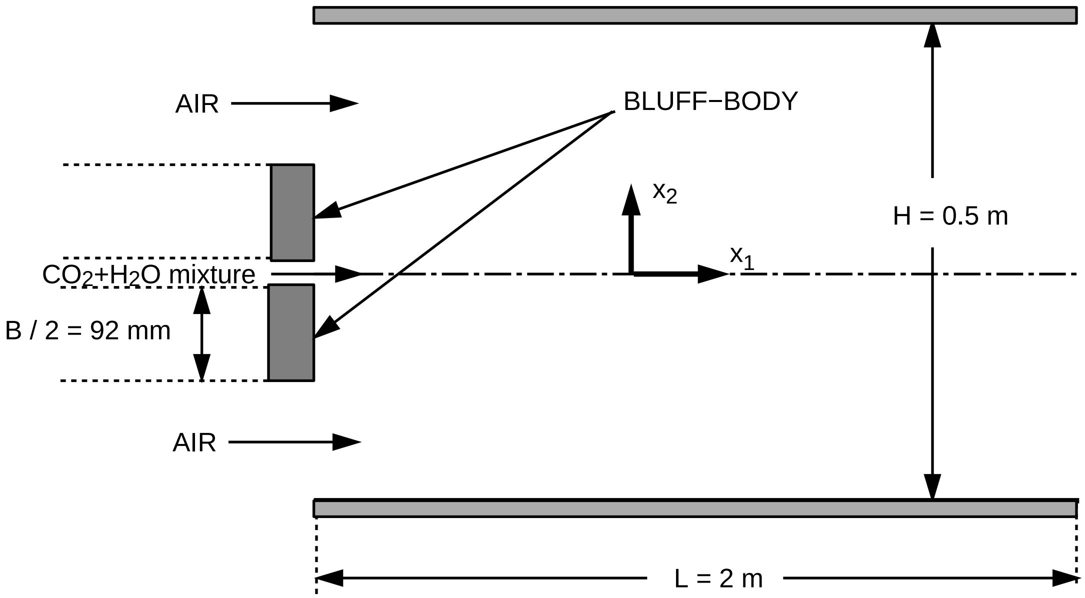

Figure 1: Geometry used for sample calculations

properties and the bluff body size is 13,304. The wake behind the bluff body promotes intense mixing by recirculation.

In order to isolate the effect of TRI, the case described above was run with radiation but without TRI, and a restart file was stored after 460 ms. The divergences of the radiative heat flux and the wall heat fluxes were calculated and stored. The TRI terms were then turned on and the simulation was allowed to march forward for a single time step of one nanosecond. The divergences and wall heat loads were recalculated. Figure 2 illustrates the divergences and wall heat fluxes with and without TRI. The exact opposite effect of what was observed for reactive flows in Ref. 1 is observed here. Figure 2(a) shows that the regions of strong emission contract to some extent when TRI is included. Consequently, the radiative wall heat fluxes decrease by approximately 10% when TRI is included [Fig. 2(b)], although the relative change is much smaller than what was observed for a flame, where an increase of about 45% was noted (Mazumder and Modest, 1997). The smaller change was expected since it is well-known that the fluctuations in a flame are significantly larger than in an inert flow. All of the above observations suggest that $\langle \kappa'_\lambda \, E'_{b\lambda} \rangle$ is negative in this case, which was indeed observed to be true when this term was printed out.

The negative magnitude of the correlation $\langle \kappa'_\lambda \, E'_{b\lambda} \rangle$ can be explained physically by examining a situation where pure carbon dioxide flows into still air. A blob of CO_2, as soon as it is exposed to the air, captures some oxygen and nitrogen, and loses some CO_2 to the surrounding air due to mixing. Consequently, the CO_2 concentration in the blob decreases. In the absence of turbulence this exchange takes place by molecular diffusion only, and is extremely slow. In the presence of turbulence the mixing proceeds at a rate governed by the local turbulent time scale, and is usually quite rapid. The important issue at this point is whether the temperature of the blob increases or decreases during this mixing process. This, of course, is governed by the relative temperature difference between the CO_2 stream and the surrounding air. If the CO_2 stream is colder than the surrounding air, which is the case here, the temperature of the blob will increase. The reverse

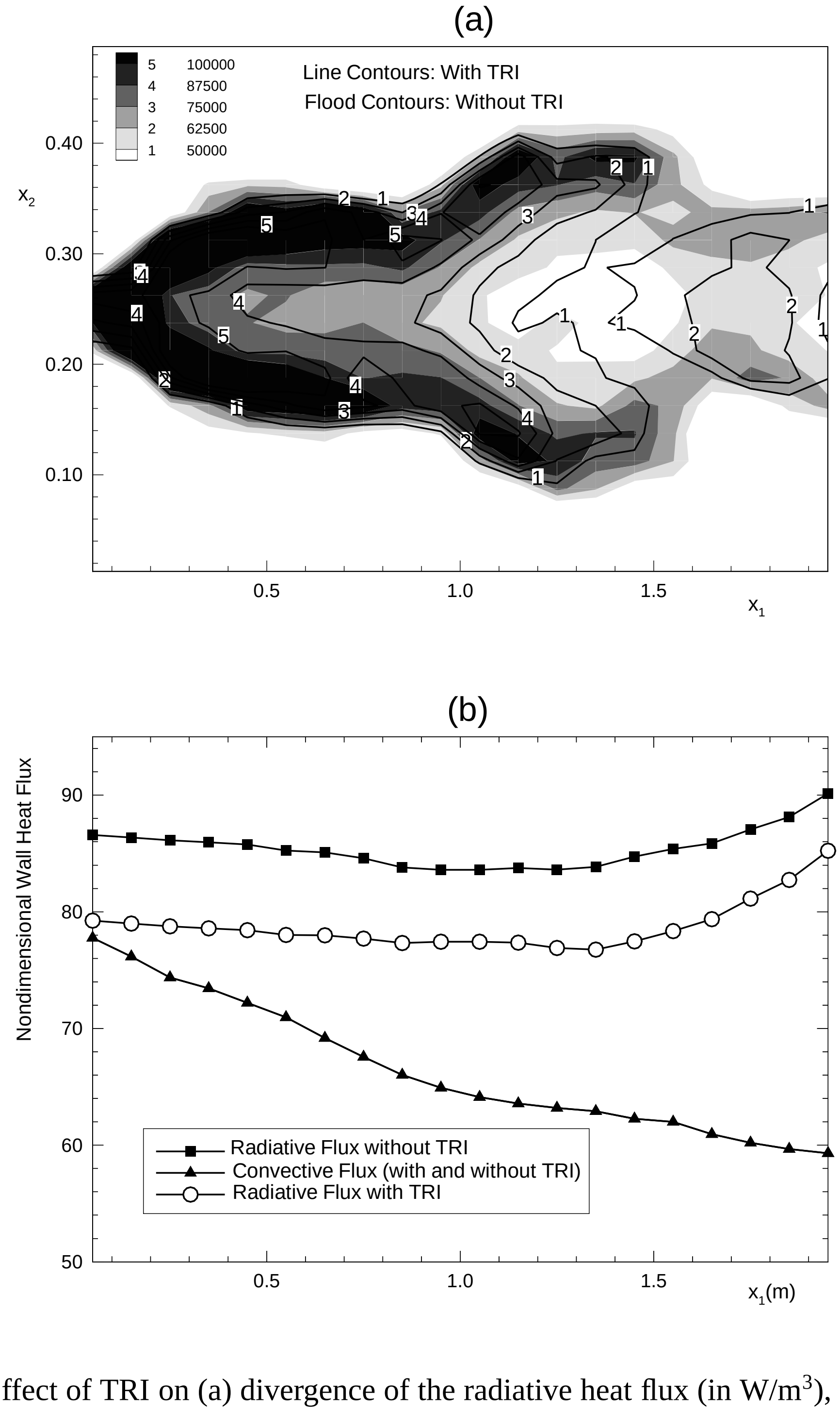

Figure 2: Effect of TRI on (a) divergence of the radiative heat flux (in W/m^3), and (b) wall heat flux for the case when the inlet coflowing air temperature is 200K higher than the inlet temperature of the CO_2–H_2O mixture

is true if an air blob is considered, *i.e.*, a positive concentration fluctuation will be associated with a negative temperature fluctuation. The net effect of these associations result in correlations such as $\langle Y_i' T' \rangle$ being negative if the surrounding or coflowing air is hotter than the species jet. By the same token, the correlation is expected to be almost zero or randomly behaving if the temperature of the two streams are equal, and positive if the CO_2–H_2O mixture stream is hotter than the coflowing air stream. To investigate this matter, two more simulations were performed. In the first case, the two inlet temperatures were maintained equal, and in the second case, the CO_2–H_2O mixture was injected at a temperature 200K hotter than the air injection temperature. The heat fluxes for these two cases have been illustrated in Fig. 3. For the case with equal inlet temperatures of the two streams, as expected, the difference in the radiative flux with and without TRI is extremely small, and may be attributed to the higher-order correlations such as $\langle Y_i' T'^2 \rangle$ and $\langle T'^3 \rangle$ [equation (3)]. When the temperature of the CO_2–H_2O mixture stream is higher than the temperature of the coflowing air, TRI plays the role of increasing the radiative wall heat flux, and this lending strong support to the above physical explanation.

In most practical situations, the exhaust gas from a combustor is a mixture of all the different species, and all species are at the same temperature, rather than existing as separate streams with different temperatures. Therefore, it is reasonable to conclude that the effect of TRI in nonreactive flows is only marginal and may be neglected to simplify the analysis.

CONCLUSIONS

The effect of turbulence-radiation interactions in nonreactive flow of combustion gases was investigated numerically. The role of TRI largely depends on how the temperature fluctuations correlate with the concentration fluctuations. In most cases of practical interest, the fluctuations were found to be uncorrelated, resulting in almost negligible effect of TRI on the wall heat loads.

Acknowledgment

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References

Kabashnikov, V.P. and Myasnikova, G.I., 1985, “Thermal Radiation in Turbulent Flows - Temperature and Concentration Fluctuations”, *Heat Transfer - Soviet Research*, Vol. 17, No. 6, pp. 116–125.

Kabashnikov, V.P., 1985, “Thermal Radiation in Turbulent Flows - in the Case of Large Fluctuations of the Absorption Coefficient and the Planck Function”, *Journal of Engineering Physics*, Vol. 49, No. 1, pp. 778–784.

Mazumder, S. and Modest, M.F., 1997, “A PDF Approach to Modeling Turbulence-Radiation Interactions in Nonluminous Flames”, *International Journal of Heat and Mass Transfer*, in press.

Mazumder, S., 1997, “Numerical Study of Chemically Reactive Turbulent Flows with Radiative Heat Transfer”, Ph.D. Thesis in Mechanical Engineering; The Pennsylvania State University.

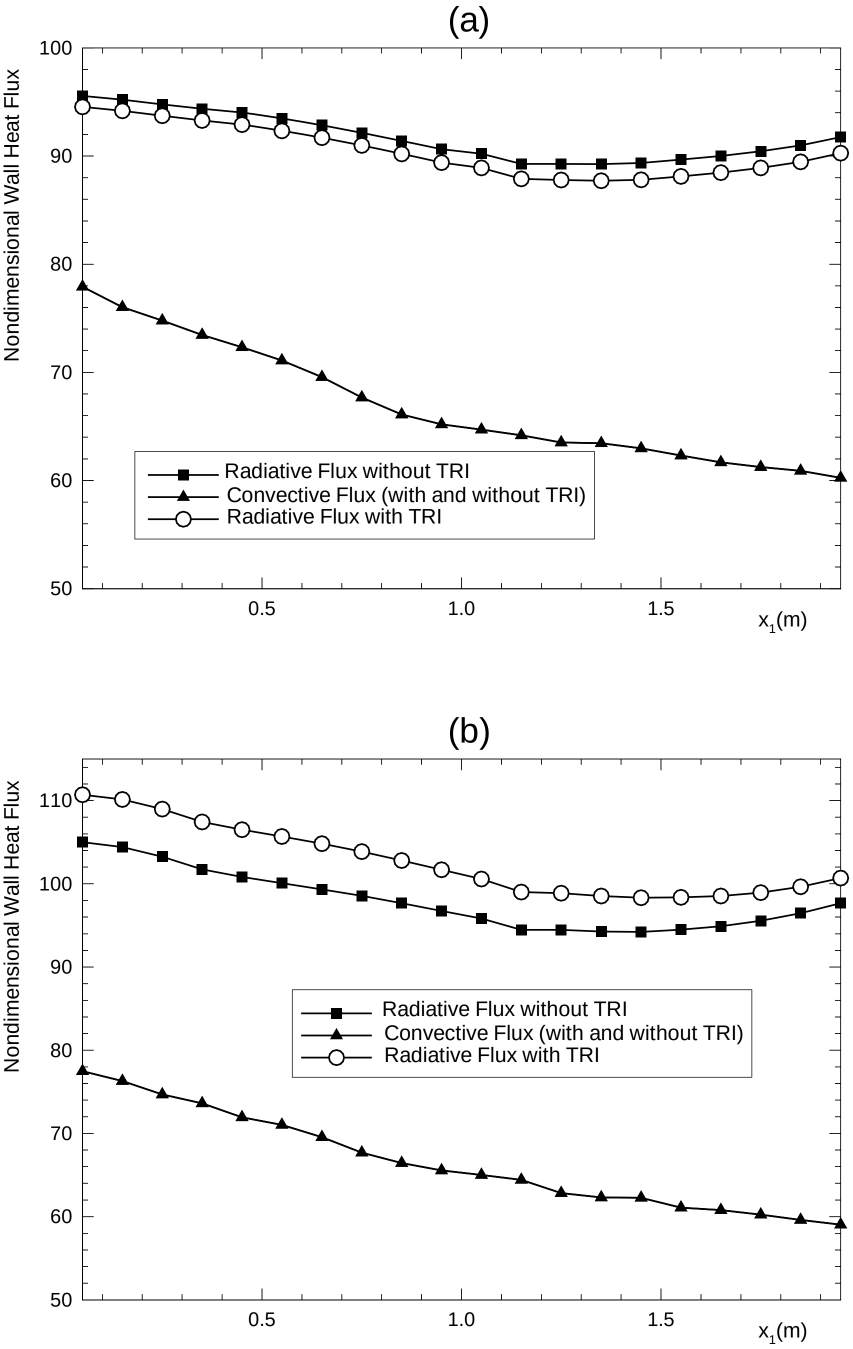

Figure 3: Effect of TRI on wall heat fluxes for (a) equal inlet temperatures for CO_2–H_2O mixture and coflowing air, and (b) inlet CO_2–H_2O mixture temperature 200K higher than coflowing air inlet temperature

Modest, M.F., 1993, *Radiative Heat Transfer*, McGraw Hill, Inc.

Pope, S.B., 1985, “PDF Methods for Turbulent Reactive Flows”, *Progress in Energy and Combustion Science*, Vol. 11, pp. 119–192.

Song, T.H. and Viskanta, R., 1987, “Interaction of Radiation with Turbulence: Application to a Combustion System”, *Journal of Thermophysics*, Vol. 1, No. 1, pp. 56–62.