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Spectrum of temperature fluctuations in high-temperature turbulent gas–particle flow

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Abstract—The effects of both the interphase convective interaction and radiative energy transfer on the spectra of temperature fluctuations are considered for homogeneous and isotropic turbulence in high-temperature, two-phase flow. The analysis is carried out for two kinds of small particles (with low Reynolds number), mainly scattering sapphire particles (Al_2O_3), and strongly absorbing coal particles. The radiative properties of the particles was calculated using Mie theory. Particles may modify the temperature spectrum of the carrier fluid by smoothing the intensity of temperature fluctuations. This effect is increased with a decrease of particle relaxation time and with an increase in particle concentration. At high temperatures, the presence of absorbing and scattering particles greatly increases the total dissipation rate due to two mechanisms: i.e. interphase convective interaction and radiative transfer. As a result, radiation modifies the spectrum of temperature fluctuations significantly, and increases the suppression of temperature fluctuations by the particles. Effects of radiation are different in various regions of wave space and depends as well on the radiative properties of particles and their concentration.

INTRODUCTION

For many years engineers and scientists have been interested in gas–solid suspension flows. In recent years, applications such as solid propellant rockets, air pollution problems, and many metallurgy, energy productions and chemical processes in industry have stimulated interest in the study of turbulent gas–particle mixtures and demonstrated the need for a better fundamental knowledge of the details of the flow. The addition of particulate matter to turbulent flows increases the complexity of phenomena and complicates theoretical treatment [1, 2]. Theoretical analyses based on the theory of turbulence spectra have been done previously [3–6]. The main conclusion is that the presence of particles, with a low particle Reynolds number, tends to suppress turbulence of the carrier fluid. Additional complexity arises in cases where radiation is important. The first computations of the smoothing of geophysical or astrophysical temperature fluctuations by radiative transfer [7–9] clearly demonstrated the existence of a radiative dissipation mechanism for the turbulent temperature variance in the planetary boundary layer. More details have been provided by Coantic and Simonin [10]. Knowledge of thermal fluctuation spectra is often required for better understanding and modeling of turbulent flows (second-order closure for example). High-temperature systems usually include radiating gases such as CO_2 and H_2O, and radiative transfer in these systems acts as a dissipative process, especially for large-sized structures where the optical thickness becomes large. Attention was paid in the literature to the influence of turbulence on radiation since this is important for simulating radiation from turbulent flames. Both theoretical and experimental studies have shown that the emitted radiation from the flame may be significantly increased by temperature fluctuations [11–16]. Comparatively little attention has been paid to the effects of radiation on temperature fluctuations in high-temperature media. Recently Soufiani [17, 18] considered the temperature fluctuation spectrum for high-temperature radiating gases (CO_2, H_2O). But cases in which a gas carries a significant amount of emitting, absorbing and scattering particles have not been considered. The latter can modify the spectrum of temperature fluctuations even without radiation [5, 19]. This can occur in many applications, such as combustion of solid or liquid fuels, metal powder production by sprays, high-temperature thermochemical treatment of sulphide raw materials in nonferrous metallurgy, amongst others.

This research is aimed at determining the effects of radiation and interphase convective interaction on temperature fluctuation spectra of the carrier fluid for various particle concentrations. This problem is solved in a spectral space; the solution is then given for idealized homogeneous–isotropic turbulence with appropriate spectral transfer assumptions. The analysis is carried out for small temperature fluctuations in such a way that the blackbody intensity may be linearized around the mean temperature. Calculations

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NOMENCLATURE

A	$\frac{2}{3}Nu_p\lambda_i^0\Phi/R_p^2$
a_0	heat diffusivity
B_ν	Planck's function
c	specific heat
$\mathbf{E}$	spectral function of turbulent temperature fluctuations
h	radiative source term
I_ν	intensity of radiation
k	wave number
$\mathbf{k}$	wave vector
K_{ap}	monochromatic absorption cross-section of particle cloud
K_{sp}	monochromatic scattering cross-section of particle cloud
$P_\nu(\mathbf{r}, \mathbf{n}', \mathbf{n})$	scattering phase function
$\mathbf{r}$	radius vector
R_p	radius of particle
T	temperature
$\mathbf{u}$	velocity vector of fluid phase
$\mathbf{v}$	velocity vector of particulate phase.

Greek symbols

α_f	monochromatic absorption coefficient of gas phase
β	mass particle concentration
γ	single scattering albedo
ε	turbulent dissipation rate
λ^0	conductivity of the fluid phase
ν	viscosity; frequency of radiation
σ_0	Stefan–Boltzmann constant
τ	particle relaxation time for heat
Φ	volume particle concentration
ω	solid angle.

Subscripts

f	refers to fluid
p	refers to particle.

have been made for two kinds of particles: mainly scattering particles of sapphire (Al_2O_3) and strongly absorbing particles of coal.

EQUATIONS FOR THE TEMPERATURE SPECTRA IN TWO-PHASE FLOWS

In the following analysis we assume that:

1. the turbulence is homogeneous and isotropic;
2. the particles are small (i.e. their Reynolds number is low) so that the particle Nusselt number $Nu_p = 2$;
3. the volume particle concentration Φ is small and fluctuations of particle concentration are ignored;
4. since the distance between particles is substantially larger than the particle size, particle collisions are ignored;
5. the fluctuating component T_f' of the carrier fluid temperature is small compared with the mean temperature $\bar{T}_f$. The same assumption has been made for particle temperature T_p'. These assumptions enable us to do a linear decomposition of the black-body intensity $I_{b\nu}$ with T' (see discussion by Soufiani [18]);
6. the particles are monodisperse;
7. the mean temperatures of both phases are approximately equal, $\bar{T}_f \approx \bar{T}_p$, since particle sizes are small;
8. the variances of particle fluctuating temperatures are caused mainly by the convective interphase interaction (small particles); and
9. the fluid and particle properties are constant.

With these assumptions the energy equations for both phases can be written as simple equations for temperatures:

Carrier phase

$$c_f\rho_f\left(\frac{\partial T_f}{\partial t}+\mathbf{u}\frac{\partial T_f}{\partial \mathbf{r}}\right) = \lambda_f^0\frac{\partial^2 T_f}{\partial \mathbf{r}^2} - A(T_f - T_p) + h; \quad (1)$$

Dispersed phase

$$\Phi c_p\rho_p\left(\frac{\partial T_p}{\partial t}+\mathbf{v}\frac{\partial T_p}{\partial \mathbf{r}}\right) = A(T_f - T_p). \quad (2)$$

The radiative heating (or cooling) rate is expressed as an integral over the electromagnetic wave frequencies ν, and direction $\mathbf{n}$, of the variations in the monochromatic specific intensity $I_\nu(\mathbf{r}, \mathbf{n})$:

$$h = \int_0^\infty \int_\omega K_\Sigma\{I_\nu(\mathbf{r},\mathbf{n}) - [(1-\gamma_\nu)\,B_\nu(T) + \gamma_\nu J_{s\nu}]\}\,d\omega\,d\nu. \quad (3)$$

The value K_Σ is the monochromatic extinction cross-section of a gas–particle mixture:

$$K_\Sigma = \alpha_f + K_{ap} + K_{sp} \quad \gamma_\nu = K_{sp}/K_\Sigma. \quad (4)$$

The scattering source function $J_{s\nu}$ can be written in the usual form:

$$J_{s\nu} = \frac{1}{4\pi}\int_{4\pi} P_\nu(\mathbf{r},\mathbf{n}',\mathbf{n})\,I_\nu(\mathbf{r},\mathbf{n}')\,d\omega. \quad (5)$$

In turbulent flows it is customary to separate the variables into their average and fluctuating components, i.e.

$$T_f = \bar{T}_f + T_f' \quad \mathbf{u} = \bar{\mathbf{u}} + \mathbf{u}',$$
$$T_p = \bar{T}_p + T_p' \quad \mathbf{v} = \bar{\mathbf{v}} + \mathbf{v}' \quad h = h + h'.$$

Classical manipulation of equations (1) and (2) leads to equations for mean values and fluctuating components. Having done that, we get equations for the fluctuating components as follows:

$$\frac{\partial T_f'}{\partial t}+\bar{\mathbf{u}}\frac{\partial T_f'}{\partial \mathbf{r}}+\mathbf{u}'\frac{\partial \bar{T}_f}{\partial \mathbf{r}}+\mathbf{u}'\frac{\partial T_f'}{\partial \mathbf{r}}-\overline{\mathbf{u}'\frac{\partial T_f}{\partial \mathbf{r}}} = a_0\frac{\partial^2 T_f'}{\partial \mathbf{r}^2}-\frac{1}{\tau_p}\frac{c_p}{c_f}\beta(T_f'-T_p')+h', \quad (6)$$

$$\frac{\partial T_p'}{\partial t}+\bar{\mathbf{v}}\frac{\partial T_p'}{\partial \mathbf{r}}+\mathbf{v}'\frac{\overline{\partial T_p}}{\partial \mathbf{r}}+\mathbf{v}'\frac{\partial T_p'}{\partial \mathbf{r}}-\overline{\mathbf{v}'\frac{\partial T_p'}{\partial \mathbf{r}}}=\frac{1}{\tau_p}(T_f'-T_p'), \quad (7)$$

where $\tau_p = R_p^2\rho_p c_p/3a_0\rho_f c_f$ is the particle relaxation time for heat. In these equations, h', which interacts with the fluctuating temperature field, represents the radiative heating rate due to fluctuating temperatures, through the Planck function or radiative properties of the phases.

Introducing the additional assumption that a characteristic scale of variations of mean parameters is much larger than a turbulent scales, we can neglect the third terms on the l.h.s. of equations (6) and (7). Furthermore, we use a formalism similar to that of Coantic and Simonin [10] to obtain the equation for the temperature spectrum. Equations (6) and (7) are then written in a simpler form:

$$\frac{\partial T_f'}{\partial t}+\mathbf{u}'\frac{\partial T_f'}{\partial \mathbf{r}}=a_0\frac{\partial^2 T_f'}{\partial \mathbf{r}^2}-\frac{1}{\tau_p}\frac{c_p}{c_f}\beta(T_f'-T_p')+h' \quad (8)$$

$$\frac{\partial T_p'}{\partial t}+\mathbf{v}'\frac{\partial T_p'}{\partial \mathbf{r}}=\frac{1}{\tau_p}(T_f'-T_p'), \quad (9)$$

where β is the mass particle concentration (kg/kg).

The three-dimensional Fourier transform,

$$\hat{\Psi}(\mathbf{k}) = (2\pi)^{-3}\int_{R^3}\exp(-i\mathbf{k}\cdot\mathbf{r})\Psi(\mathbf{r})\,d\mathbf{r}$$

of equations (8) and (9) leads to:

$$\frac{\partial \hat{T}_f'(\mathbf{k},t)}{\partial t} = -ik\hat{\mathbf{u}}(\mathbf{k},t)\otimes\hat{T}_f'(\mathbf{k},t)-a_0k^2\hat{T}_f'(\mathbf{k},t) -\frac{c_p}{c_f}\frac{1}{\tau_p}\beta(\hat{T}_f'-\hat{T}_p')-N(k)\hat{T}_f', \quad (10)$$

$$\frac{\partial \hat{T}_p'(\mathbf{k},t)}{\partial t} = -ik\hat{\mathbf{v}}(\mathbf{k},t)\otimes\hat{T}_p'(\mathbf{k},t)+\frac{1}{\tau_p}(\hat{T}_f'-\hat{T}_p'), \quad (11)$$

where $N(k)$ is the relative spectral radiative dissipation rate introduced and derived by Coantic and Simonin [10]:

$$N(k) = \int_0^\infty N_\nu(k)\,d\nu \quad N_\nu(k) = \frac{1}{\rho_f c_f}\overline{\hat{h}_\nu(\mathbf{k})/\hat{T}_f'(\mathbf{k})},$$

and:

$$N_\nu(k) = \frac{4\pi}{\rho_f c_f}\frac{dB_\nu}{dT}K_\Sigma\left[1-\frac{K_\Sigma}{k}\tan^{-1}\left(\frac{k}{K_\Sigma}\right)\right] \times\frac{1-\gamma_\nu}{1-\gamma_\nu\frac{K_\Sigma}{k}\tan^{-1}\left(\frac{k}{K_\Sigma}\right)}\times\left[1-\sigma_1\gamma_\nu\left(\frac{K_\Sigma}{k}\right)^2 \times\left(1-\frac{K_\Sigma}{k}\tan^{-1}\frac{k}{K_\Sigma}\right)\cdot\frac{1-\gamma_\nu}{1-\gamma_\nu\frac{K_\Sigma}{k}\tan^{-1}\left(\frac{k}{K_\Sigma}\right)}\right]^{-1}$$

$$\sigma_1 = 3\langle\cos\theta\rangle, \quad (12)$$

and $\mathbf{k}$ is the turbulent wave vector, and k is the wave number.

Multiplying equation (10) by the complex-conjugate $\hat{T}_f'(-\mathbf{k},t)$ and equation (11) by $\hat{T}_p'(-\mathbf{k},\mathbf{t})$, averaging and integrating over a spherical shell of radius $\mathbf{k}$, the equations for the turbulent temperature spectra are finally obtained as follows:

$$\frac{\partial E_f(k,t)}{\partial t}-F_f(k,t) = -2a_0k^2E_f(k,t) -2\frac{1}{\tau_p}\frac{c_p}{c_f}\beta[E_f(k,t)-E_{fp}(k,t)]-2N(k)E_f(k,t) \quad (13)$$

$$\frac{\partial E_p(k,t)}{\partial t}-F_p(k,t)=\frac{2}{\tau_p}[E_{fp}(k,t)-E_p(k,t)], \quad (14)$$

where E_f, E_p are the three-dimensional spectral functions of the turbulent temperature fluctuations for the carrier and the dispersed phases, respectively; and F_f, F_p represent the transfer terms related to the convection of temperature fluctuations. The spectral function $E_{fp}(k,t)$ is an interrelative spectral function which is expressed as:

$$E_{fp}(k,t) = \int_{\mathbf{k}(R^3)}\overline{\hat{T}_f'\hat{T}_p'}(-\mathbf{k},t)e^{ik\cdot r}\,d\mathbf{k}. \quad (15)$$

The additional equation for E_{fp} can be obtained by multiplying equation (10) by $\hat{T}_p'(-\mathbf{k},t)$ and equation (11) by $\hat{T}_f'(-\mathbf{k},t)$, averaging, integrating and adding the equations. Having done this we get:

$$\frac{\partial E_{fp}}{\partial t}-F_{fp} = -a_0k^2E_{fp}-\frac{1}{\tau_p}\frac{c_p}{c_f}\beta(E_{fp}-E_p) +\frac{1}{\tau_p}(E_f-E_{fp})-N(k)E_{fp}, \quad (16)$$

which, except for the radiation, agrees with the result found by Derevich [5]. Thus, within the framework of our assumptions, equations (13), (14) and (16) describe the dynamics of the spectral functions in the turbulent two-phase flows with an emitting, absorbing and scattering medium. In the range of the universal equilibrium in wave number space, at large enough wave numbers, the differential terms in equations (13), (14), and (16) are small compared with others [25] and the third-order correlations are small, compared with the second-order correlations. Then from equations (14) and (16), the approximate relationship follows:

$$E_{fp} \approx \frac{E_f}{1+\tau_p a_0 k^2 + \tau_p N(k)}.$$

Since at large enough wave numbers the conductive dissipation rate prevails compared with the radiative one [18] and the latter equation transforms to the result by Derevich [5]:

$$E_{fp} \approx \frac{E}{1+\tau_p a_0 k^2}. \quad (17)$$

Substitution of equation (17) into equation (13) leads to the simple equation:

$$\frac{\partial E_f(k,t)}{\partial t} - F_f(k,) = -2a_0 k^2 E_f(k,t)\left[1+\frac{c_p}{c_f}\beta\frac{1}{1+\tau_p a_0 k^2}\right] - 2N(k)E_f(k,t). \quad (18)$$

It is seen from equation (18) that interphase convective heat transfer acts as an additional dissipative process dependent on the particle mass concentration β, ratio of specific heats of phases and particle sizes. Radiation acts as a dissipative mechanism, just like thermal molecular conduction expressed in terms of $a_0 k^2$. The presence of particles increases the turbulent dissipation of temperature fluctuations in two-phase flow, compared with single-phase flow, because the energy flux from large eddies to smaller ones is increased.

The dynamic equation (18) is solved by using an Onsager-type closure presented by Hill [20]:

$$F_f(k) = -\frac{\partial}{\partial k}[\sigma(k)E_f(k)], \quad (19)$$

where $\sigma(k)$ depends only on dynamic conditions and is assumed to be unmodified by radiation or by particles:

$$\sigma(k) = \frac{k}{Q}\left[\varepsilon^{-1/3}k^{-2/3} + b\left(\frac{\nu}{\varepsilon}\right)^{1/2}\right]^{-1} \quad (20)$$

where Q is Corrsin–Obukhov's constant ($Q \approx 0.68$) and b is a parameter which Hill assumes is equal to 2.5. The validation of using of this closure is discussed by Coantic and Simonin [10] and Soufiani [18].

For steady-state conditions, the solution of equations (18)–(20) can be written as:

$$E_T(k) = E_f(k) = \psi k^{-5/3}\varepsilon^{-1/3}\left(1+k^{2/3}b\varepsilon^{1/3}\sqrt{\frac{a_0\,Pr}{\varepsilon}}\right) \times \exp\left[-2\int_0^k \frac{a_0 k'^2 + \frac{c_p}{c_f}\beta\frac{a_0 k'^2}{1+\tau_p a_0 k'^2} + N(k')}{\sigma(k')}\,dk'\right] \quad (21)$$

where ψ is an integration constant. Assuming that, in the limit $k \to 0$, the inertio-convective form, $E_T(k) = Q\chi\varepsilon^{-1/3}k^{-5/3}$, is recovered. Then $\psi = \chi$, where χ is the total temperature dissipation rate:

$$\chi = 2\int_0^\infty \left(a_0 k^2 + \frac{c_p}{c_f}\beta\frac{a_0 k^2}{1+\tau_p a_0 k^2} + N(k)\right)E_T(k)\,dk. \quad (22)$$

Validation of this approach is given by Coantic and Simonin [10] and Soufiani [18]. In the case without radiation, equation (21) becomes:

$$E_T(k) = \psi\varepsilon^{-1/3}k^{-5/3}\left[1+bk^{2/3}\varepsilon^{1/3}\left(\frac{a_0 Pr}{\varepsilon}\right)^{1/2}\right] \times \exp\left\{-2\int_0^k a_0 k'^2\left[1+\frac{c_p}{c_f}\beta\frac{1}{1+\tau_p a_0 k'^2}\right]\sigma^{-1}(k')\,dk\right\}. \quad (23)$$

TEMPERATURE SPECTRUM OF THE CARRIER FLUID

Calculations have been performed for two kinds of particles: strongly scattering Al_2O_3 particles and strongly absorbing coal particles. Mie theory is used for calculations monochromatic extinction, absorption, scattering cross-sections for single particles as well as the mean $\langle\cos\theta\rangle$ of the phase scattering function. Since particle concentrations are small, the global radiative properties of the particle clouds are obtained by a simple integration. The complex refractive index for Al_2O_3 particles was taken from Rubzov *et al.* [21]: $n = 1.8 - i\times 0.0158$ in wavelength range $\Delta\lambda = 0.3$–0.4 μm; $n = 1.78 - i\times 0.00563$ in $\Delta\lambda = 0.4$–0.6 μm; $n = 1.75 - i\times 0.002$ in $\Delta\lambda = 0.6$–1.1 μm; $n = 1.7 - i\times 0.0016$ in $\Delta\lambda = 1.1$–1.3 μm; $n = 1.55 - i\times 0.0016$ in $\lambda > 1.3$ μm.

The complex refractive index for coal particles was set $n = 1.9 - i\times 0.24$ from data by Blokh [22]. Some computed radiative properties for both kinds of particles are shown in Figs. 1 and 2. In the temperature spectrum computation, the main calculation parameters are the thermodynamic fluid conditions (temperature, composition and phase densities), the viscous dissipation rate of turbulence kinetic energy ε, and the total dissipation rate χ, which depends on the injection rate. Once these parameters are specified, the three-dimensional spectral function $E_T(k)$ of the carrier fluid may be computed from either equation (21) or (23).

The first part of the computation is for the case in which mainly the dispersed phase is radiating, while radiation of the carrier fluid is negligible. The spectral wavelength region 0.3–20 μm was divided into 20 subregions and extinction, absorption and scattering cross-sections were averaged with the Planck's function in each interval. Preliminary identification of the spectral ranges most affected by the different

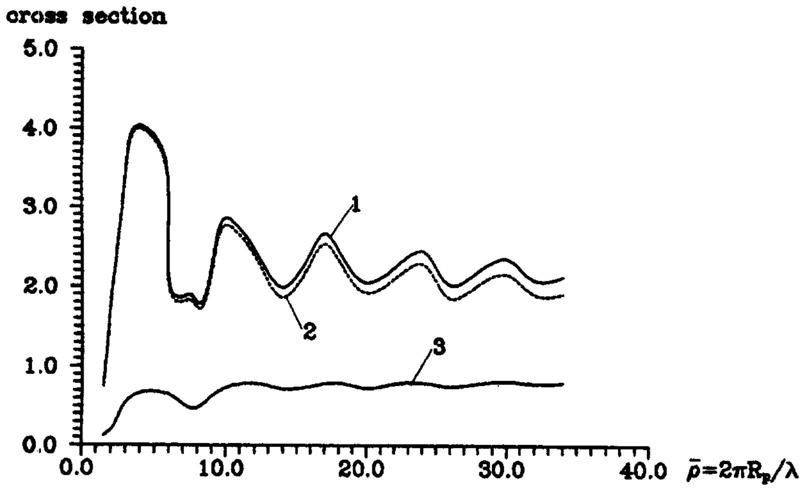

Fig. 1. Extinction (1), scattering (2) and mean cosin $\langle \cos\theta \rangle$ (3) of the phase scattering function for Al_2O_3 particles.

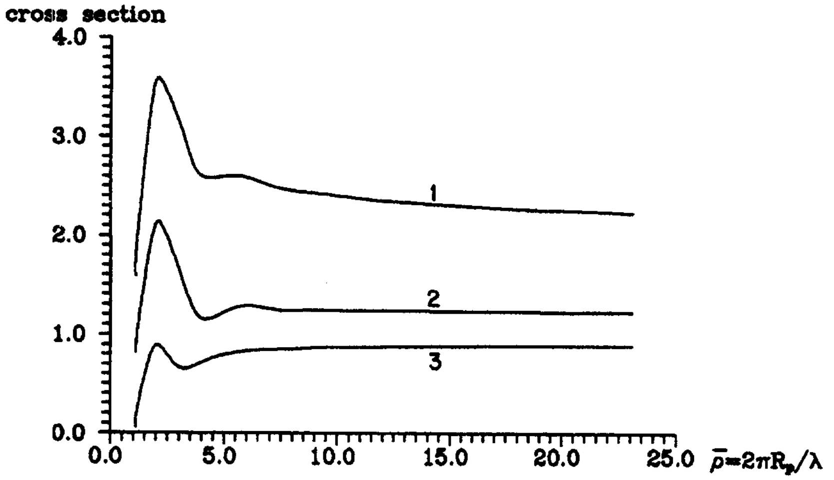

Fig. 2. Extinction (1), scattering (2) and mean cosin $\langle \cos\theta \rangle$ (3) of phase scattering function for coal particles.

processes, can be done by comparing the corresponding characteristic times as functions of wave number k. The characteristic time-scale of conductive and particle dissipation and radiative dissipation S_D, S_p and S_R, respectively, are:

$$\left.\begin{aligned} S_D^{-1} &= a_0 k^2 \\ S_p^{-1} &= \frac{c_p}{c_f}\beta\frac{a_0 k^2}{1+\tau_p a_0 k^2} \\ S_R^{-1} &= N(k) \end{aligned}\right\} \quad (24)$$

Calculation results from equation (24) are shown in Figs. 3 and 4 for Al_2O_3 and coal particles, respectively. A contribution S_p^{-1} of the dispersed phase to the general dissipation rate depends on the particle concentration, the ratio of specific heat of the phases and of the particle relaxation time for heat transfer τ_p. In the large-scale region ($\tau_p a_0 k^2 \ll 1$) of the wave space, the dissipation rate, caused by the interphase heat transfer, is increased as k^2 and is proportional to the particle concentration. In the small-scale region ($\tau_p a_0 k^2 \gg 1$) this dissipation tends to the limit $\beta c_p c_f^{-1} \tau_p^{-1}$. The contribution S_p^{-1} of the dispersed phase to the general dissipation rate becomes much more significant when the particle relaxation time for

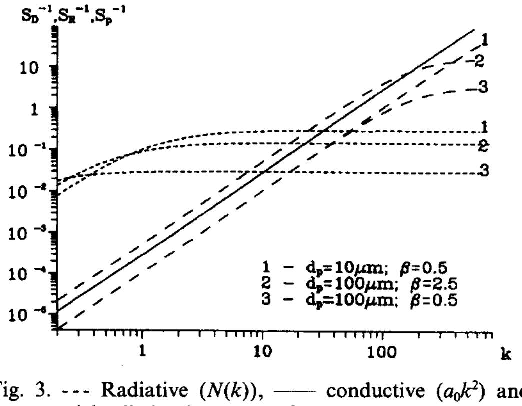

Fig. 3. --- Radiative ($N(k)$), —— conductive (a_0k^2) and ---- particle dissipation terms for turbulent temperature spectrum (Al_2O_3 particles, $T = 1500$ K).

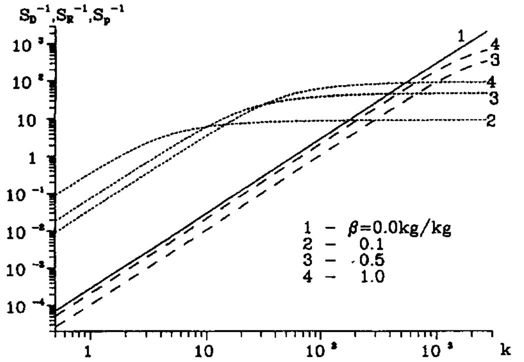

Fig. 4. --- Radiative ($N(k)$), —— conductive (a_0k^2) and — — — particle dissipation terms for turbulent temperature spectrum (coal particles, $d_p = 10\ \mu m$, $T = 1500$ K).

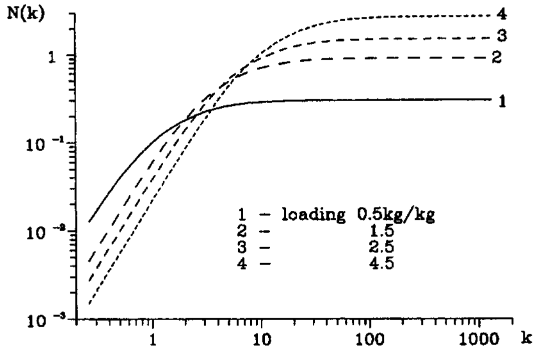

Fig. 6. Radiative dissipation terms $N(k)$ for turbulent temperature spectrum with $d_p = 10\ \mu m$ and various Al_2O_3 particle loadings.

heat τ_p is smaller than the Kolmogorov's time-scale, $\tau_\eta = (a_0/\varepsilon)^{1/2}$. It is seen that $N(k)$ is preponderant for small wave numbers (large length scales and optically thick media) while the conductive dissipation term S_D^{-1} becomes predominant compared to $N(k)$ for high values of k, which correspond to small eddies and optically thin media. For $k \to \infty$, $N(k)$ tends to a constant value. The intersection between the $N(k)$ and the $S_D^{-1}(k)$ curves is dependent on temperature, particle concentration, particle diameter and the radiative properties of the particle material, and is located near $k \approx 20$ for Al_2O_3 (mainly scattering particles with mean $\gamma > 0.9$) and near $k \approx 4.0$ for coal particles (strongly absorbing particles with $\gamma < 0.5$ in the close infrared region).

Figure 5 shows the computed spectra of the carrier phase with Al_2O_3 particles for $\varepsilon = 1$ with $T = 1500$ K, a particle diameter of 10 μm, at various particle concentrations. Calculations accounting for radiation and not accounting for radiation are displayed on this figure. The presence of particles in a flow without radiation modifies the spectral structure between $10^{-2}k_d$ and k_d, where k_d designates the Kolmogorov wave number. This modification is caused by interphase heat transfer of fluctuating motions and is found to increase with increasing particle loading. It is observed that radiation does not affect the large-scale region of turbulence (the small k region), since the spectrum is dominated by production and transfer mechanisms in this region. However, radiation radically modifies the spectral structure between $10^{-2}k_d$ and k_d. The inversion of curves with radiation can be explained by the results in Fig. 6, which shows the radiative dissipation term $N(k)$ at various particle concentrations. In the small-scale region (large wave numbers) the optical thickness $K_\Sigma k^{-1}$ (k^{-1} may be regarded as a characteristic size of turbulent eddies) is significantly smaller than unity and $N(k)$ is proportional to $K_\Sigma \approx \beta$, as follows from the asymptotic regime of equation (12). In the large-scales region (small wave numbers), the optical thickness $K_\Sigma k^{-1}$ of turbulent eddies is much larger than unity. In this case radiation of the inside parts of the volume of a large eddy is screened by its external layers and $N(k)$ is inversely proportional to optical thickness $K_\Sigma k^{-1}$ (proportional to particle concentration since $K_\Sigma \propto \beta$). This also follows from the asymptotic regime of equation (12).

Figure 7 shows computed spectra for various particle sizes. Crossing of the curves can be explained,

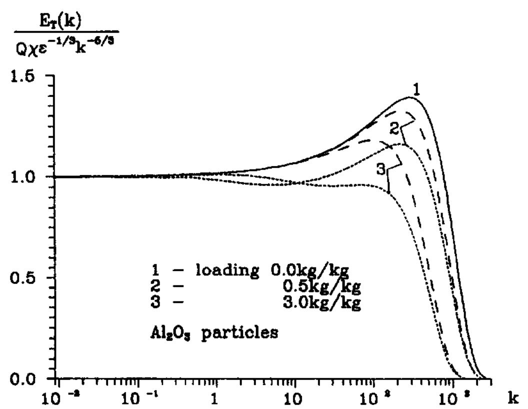

Fig. 5. Compensated thermal turbulence spectra --- with and — — — without radiation and $d_p = 10\ \mu m$.

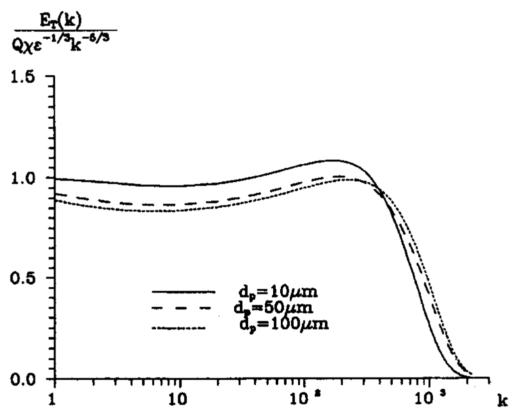

Fig. 7. Compensated thermal turbulence spectra with radiation at Al_2O_3 particle concentration = 1.0 kg/kg.

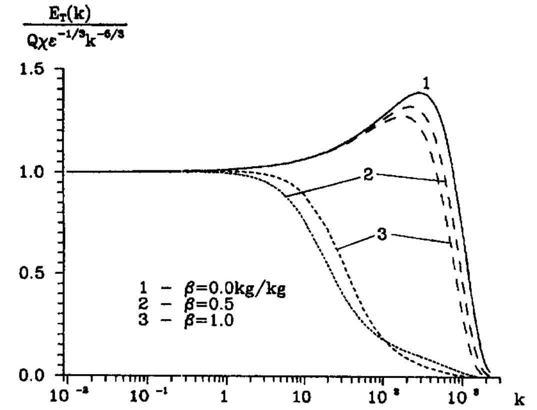

Fig. 8. Compensated thermal turbulence spectra --- with and ––– without radiation (coal particles, $d_p = 10\ \mu m$).

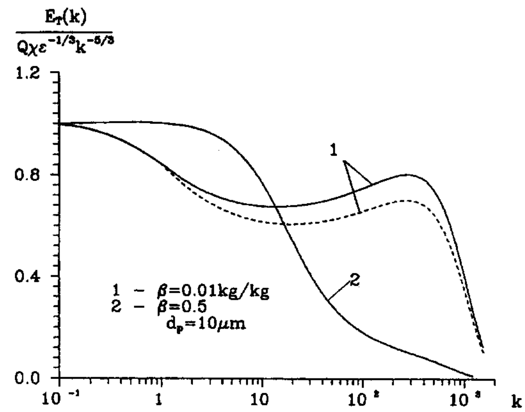

Fig. 10. Compensated thermal turbulence spectra with radiation (—— coal particles, ––– coal particles + gaseous combustion products).

because extinction cross-sections K_Σ of the particle clouds are inversely proportional to particle sizes.

Computed turbulent thermal spectra of the carrier fluid with coal particles at $T = 1500$ K and at $\varepsilon = 100$ are shown in Fig. 8. It is seen that radiation of the coal particles modifies the thermal spectra much more than the sapphire particles. Noncompensated thermal turbulent spectra, with all mechanisms (conduction, interphase convective heat transfer, radiation) for both particles kinds ($T = 1500$ K, $\varepsilon = 100$) are shown in Fig. 9. Temperature turbulent fluctuations are decreased with an increase in the parameter $\beta c_p/c_f$. In the case of lightly radiating particles, visible deviation from the $-5/3$ low occurs at $k \approx 10^2$. However, in the case of strongly absorbing coal particles, the deviation starts at $k \approx 10$. Thus, the presence of particles in the flow decreases the intensity of turbulent temperature fluctuations in the convective and the diffusion regions, and diminishes the $k^{-5/3}$-range in wave number space. Radiation increases this effect especially at the small dissipation rate ε.

In the previous discussion the carrier fluid was like a nonradiating gas, but in reality, such as in combustion media, the gas is radiating. Figure 10 depicts thermal turbulent spectra when the carrier gas consists of combustion products at 1 bar and $T = 1500$ K. The mole fractions of CO_2 and H_2O are 0.08 and 0.14, respectively. The absorption coefficients of the gas as a function of wave number ν are taken from Im and Ahluwalia [23]. Extinction and scattering cross-sections of the gas–particle mixture are calculated by summarizing the absorption coefficients of both phases in frequency bands. This estimation is not as accurate as the approach of In and Ahluwalia [23] but this is not of crucial importance in the present qualitative analysis. Radiation of gaseous combustion products is affected by small particle concentrations. At a particle loading $\beta = 0.5$, the radiation of the gas phase is already negligible (curves 2 coincide), because radiation of the gas is significantly smaller than that of coal particles. This was also pointed out by Tabanfar and Modest [24]: namely, that for an optical thickness of the particle cloud on the order of unity, particle radiation is dominant and addition of gas beyond an optical thickness of order 10 has little effect.

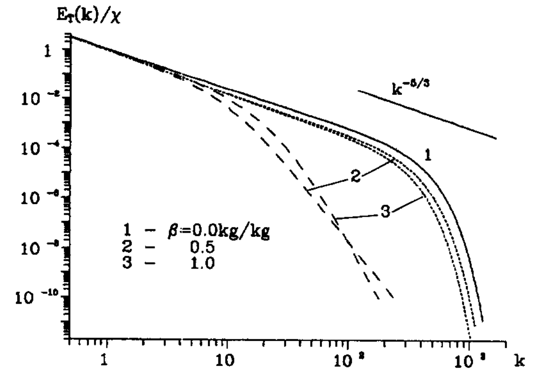

Fig. 9. Noncompensated thermal turbulent spectral functions for flows --- with Al_2O_3 particles and ––– coal particles ($d_p = 10\ \mu m$).

CONCLUDING REMARKS

It has been shown that the presence of particles with low particle Reynolds numbers may modify the structure of the temperature spectra of the carrier fluid, by smoothing the intensity of temperature fluctuations. Such smoothing is caused by interphase heat transfer, and is increased by a decrease of the particle relaxation time τ_p and by an increase of the parameter $\beta c_p/c_f$. At high temperatures, the presence of absorbing and scattering particles greatly increases the total dissipation rate that is caused by both mechanisms; namely, interphase convective and radiative heat transfer. As a result, radiation increases the suppression of turbulent temperature fluctuations by particles. For large single scattering albedo (Al_2O_3) the radiation of particles has little effect on the temperature spectra at a large dissipation rate ε of turbulent kinetic energy, but it becomes significant at small ε. In the case of strongly absorbing particles with a small single scattering albedo (for example coal particles), radiative effects become significant at large ε, which is characteristic of combustion systems. When particle concentration increases (or particles sizes decrease), the radiative dissipation $N(k)$ increases for small-sized eddies, and $N(k)$ decreases for large-sized eddies, as a result of a decrease in the optical penetration length. Finally, it should be pointed out that the presence of radiating particles in turbulent flows suppresses temperature fluctuations, and this in turn influences turbulent heat transfer coefficients.

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REFERENCES

1. G. Hetsroni, Particle–turbulence interaction, *Int. J. Multiphase Flow* **15,** 735–746 (1989).
2. L. P. Yarin and G. Hetsroni, Turbulence intensity in dilute two-phase flows, part 2, temperature fluctuations in particle laden dilute flows, *Int. J. Multiphase Flow* **20,** 17–25 (1994).
3. Yu. Buyevich and Yu. Gupalo, About influence of particles on a decay of homogeneous turbulence, *J. Appl. Mech. Phys.* **4,** 89–96 (1965).
4. P. S. H. Baw and B. L. Peskin, Some aspects of gas–solid suspension turbulence, *Trans ASME, J. Basic Engng* **39,** 631–635 (1971).
5. I. B. Derevich, Velocity and temperature turbulent spectrums in turbulent gas–solid flow, *J. Engng Phys.* **55,** 26–33 (1988).
6. F. N. Lisin and A. G. Shuklin, Analysis of spectral turbulence in two-phase flows, *J. Engng Phys.* **55,** 902–906 (1988).
7. R. M. Goody, The influence of radiative transfer on cellular convection, *J. Fluid Mech.* **1,** 124–435 (1956).
8. E. A. Spiegel, The smoothing of temperature fluctuations by radiative transfer, *Astrophys. J.* **126,** 202–207 (1957).
9. A. A. Townsend, The effects of radiative transfer on turbulent flow of a stratified fluid, *J. Fluid Mech.* **4,** 363–375 (1958).
10. M. Coantic and O. Simonin, Radiative effects on turbulent temperature spectra and budgets in the planetary boundary layer, *J. Atmos. Sci.* **41,** 2629–2651 (1984).
11. V. P. Kabashnikov and G. I. Kmit, Influence of turbulent fluctuations on thermal radiation, *J. Appl. Spectrosc.* **31,** 963–967 (1979).
12. Yu. A. Popov, An influence of temperature fluctuations on radiation in flames and the method of inverse spectral lines, *J. Thermophys. High Temp.* **18,** 383–386 (1980).
13. S. M. Jeng, M. C. Lai and G. M. Faeth, Nonluminous radiation in turbulent buoyant axisymmetric flames, *Combust. Sci. Tech.* **40,** 41–43 (1984).
14. G. M. Faeth, Heat and mass transfer in flames. *Proceedings of the Eighth International Heat Transfer Conference*, San Francisco, Vol. 1, pp. 151–160 (1986).
15. J. P. Gore, S. M. Jeng and G. M. Faeth, Spectral and total radiation properties of turbulent hydrogen/air diffusion flames, *J. Heat Transfer* **109,** 165–171 (1987).
16. T. H. Song and R. Viskanta, Interaction of radiation with turbulence: application to a combustion system, *J. Thermophys.* **1,** 56–62 (1987).
17. A. Soufiani, P. Mignon and J. Taine, Radiation–turbulent interaction in channel flow of infrared active gases. In *Ninth International Heat Transfer Conference* (Edited by G. Hetsroni), Jerusalem, Israel, Vol. 6, pp. 403–408 (1990).
18. A. Soufiani, Temperature turbulence spectrum for high-temperature radiating gases, *J. Thermophys.* **5,** 489–494 (1991).
19. F. N. Lisin, Turbulent heat diffusion in diluted dispersed flows, *J. Engng Phys.* **54,** 746–752 (1988).
20. R. J. Hill, Models of the scalar spectrum for turbulent advection, *J. Fluid Mech.* **88,** 541–562 (1978).
21. N. A. Rubzov, A. A. Emelianov and N. N. Ponomarev, Investigations of refractive index of the oxide of aluminium at high temperatures, *Thermophys. High Temp.* **22,** 294–297 (1984).
22. A. G. Blokh, Heat transfer in steam boiler furnaces, *Energoatomizdat*, Leningrad (1984).
23. K. H. Im and R. K. Ahluwanlia, Radiation properties of coal combustion products, *Int. J. Heat Mass Transfer* **36,** 293–302 (1993).
24. S. Tabanfar and M. F. Modest, Combined radiation and convection in absorbing, emitting, nongray gas–particulate tube flow, *J. Heat Transfer* **109,** 478–484 (1987).
25. A. C. Monin and A. M. Yaglom, *Statistical Hydrodynamic, Part* II. Izd. Nauka, Moscow (1967).