RADIATION STATISTICS IN HOMOGENEOUS ISOTROPIC TURBULENCE

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INTRODUCTION

The interaction between turbulence and radiation (TRI) is a relevant issue in turbulent reactive flows, yielding a significant increase of the radiative heat fluxes in comparison with laminar flows [1, 2]. However, our knowledge about such interaction is still limited. Direct numerical simulation (DNS) provides fundamental and reliable insight on turbulent flows, but it can only be applied to simple geometries and low Reynolds number flows, because of the high computational requirements. Recently, DNS has been used to investigate TRI in simple premixed and diffusion combustion systems [3, 4]. Furthemore, we have reported statistical data of the radiation intensity field a homogeneous isotropic turbulent non-reactive flow using a pseudo-spectral code for the DNS, and a ray tracing method along with a statistical narrow band model for the radiative transfer calculations [5]. However, some features of the radiative calculations reported in [5] were not fully consistent with the requirements of the flow simulation, such as the definition of the boundary conditions, and the dependence of the statistical data on the number of samples was not investigated. These drawbacks are eliminated in the present work.

THEORETICAL ANALYSIS

The DNS calculations were carried out using a standard pseudo-spectral code in which the temporal advancement is made with an explicit 3rd order Runge-Kutta scheme [6]. The physical domain is a periodic cubic box of side 2π. The instantaneous field of a passive scalar is taken from the DNS simulation of statistically steady (forced) homogeneous isotropic turbulence using a uniform mesh with 192^3 grid nodes. The analysis was performed using up to 40 instantaneous fields after all the turbulence quantities are statistically stationary. Details of the simulation may be found in [7].

The radiative transfer calculations are performed using also a cubic box. The length of the side, L, is taken as the ratio of the optical thickness of the medium, which is prescribed, to the Planck mean absorption coefficient. Data from the flow domain are rescaled into the radiation domain as reported in [5]. The radiative properties of the medium are evaluated using the correlated k-distribution (CK) method. The integration of the radiative transfer equation along a line of sight yields

$$I_{i,\Delta\nu_k}(s) = I_{i,\Delta\nu_k}(0)\exp\left[-\int_0^s k_i(s^*)\,ds^*\right] + \int_0^s k_i(s^*)\,I_{b,\Delta\nu_k}(s^*)\;\exp\left[-\int_{s^*}^s k_i(s^{**})\,ds^{**}\right]ds^* \qquad (1)$$

where k_i is the absorption coefficient associated with the ith quadrature point, and $\Delta\nu_k$ is the kth wavenumber interval length. The radiation intensity entering the calculation domain at $s = 0$ is not prescribed, but determined to enforce that the entering intensity is equal to the leaving intensity, i.e., $I_{i,\Delta\nu_k}(L) = I_{i,\Delta\nu_k}(0)$. The integrals in Eq. (1) are numerically evaluated using Simpson's rule, and the parameters of the CK method are interpolated from the tabulated data using cubic splines in order to keep the order of accuracy of the radiative calculations consistent with the order of accuracy of the DNS solver (see [5] for details).

Under the conditions of homogeneous and isotropic turbulence, the statistical data computed from a temporal series of scalar data along a single optical path parallel to a coordinate axis is identical to the statistical data calculated from all optical paths parallel to the coordinate axes at a given time. The statistical data reported below was obtained from the DNS data, using all the available optical paths parallel to the coordinate axes, which are statistically indistinguishable. This means that $6\times192^2\times N_t \approx 2.2\times10^5\times N_t$ samples are used to obtain the results described below, N_t being the number of instantaneous fields considered.

RESULTS

The radiative transfer calculations were carried out assuming that the mean temperature of the medium is 1500 K, and that the medium is a mixture of CO_2 and N_2, the mean mole fraction of CO_2 being 0.10. The rms of temperature and CO_2 mole fraction were taken as 150 K and 0.01, respectively. The optical thickness of the medium is equal to one. It was further assumed that the temperature and the absorbing species fields are fully correlated.

Figure 1 shows the normalized values of the mean, rms, skewness and flatness of the radiation intensity leaving the computational domain as a function of the number of instantaneous fields, which are defined as follows, respectively:

$$\bar{I}/I_b\left(\bar{T}\right) \qquad \left(\overline{I'^2}\right)^{1/2}\Big/\bar{I} \qquad \overline{I'^3}\Big/\left(\overline{I'^2}\right)^{3/2} \qquad \overline{I'^4}\Big/\left(\overline{I'^2}\right)^{2} \tag{2}$$

The results show that N_t = 1 is not enough to obtain statistically independent results, but when N_t exceeds 20 to 25 the influence of N_t on the results becomes marginal. The probability density functions of the radiation intensity and Planck mean absorption coefficient, which are given in Fig. 2 for N_t = 40, confirm good convergence of the results and that the shape of the two pdfs is similar. The joint pdf of the radiation intensity and the Planck mean absorption coefficient is shown in Fig. 3. It is important to stress that the Planck mean absorption coefficient is a local quantity, while the radiation intensity is not, depending on the temperature and absorption coefficient along the optical path. Accordingly, it is not surprising that the computed correlation coefficient between these two quantities (-0.50) is not large. The ratio of $\overline{\kappa I}$ to the product $\bar{\kappa}\bar{I}$ is equal to 0.986, which yields $\overline{\kappa' I'}\big/\overline{\kappa I} = -0.014$. This means that the correlation $\overline{\kappa' I'}$, which is often neglected in studies of turbulence radiation interaction, is actually small for the studied conditions. Further results for selected bands and for different conditions (mean and variance of temperature and CO_2 mole fraction) will be presented in the poster.

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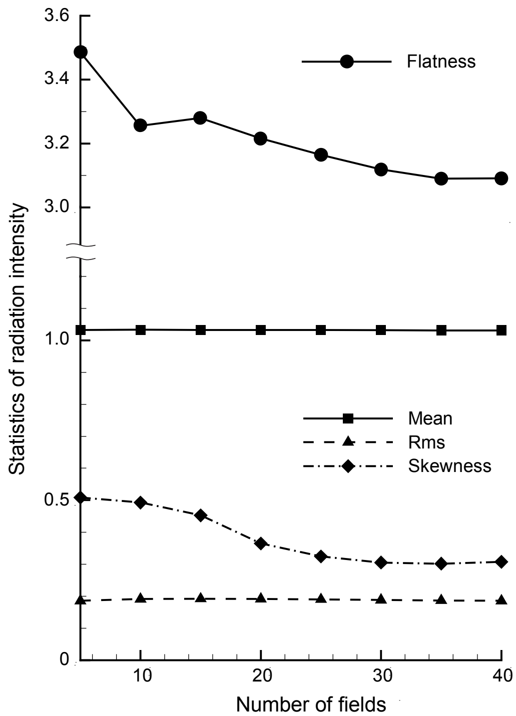

Figure 1 - Normalized values of the mean, rms, skewness and flatness of the radiation intensity leaving the computational domain as a function of the number of instantaneous fields.

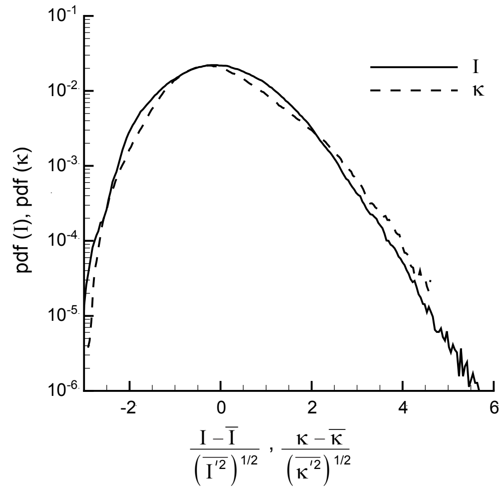

Figure 2 - Probability density functions of the radiation intensity and Planck mean absorption coefficient.

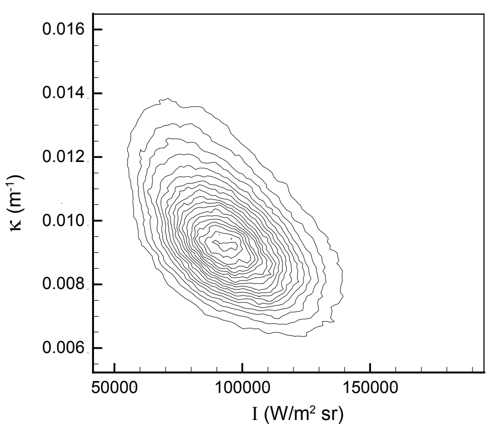

Figure 3 - Joint pdf of the radiation intensity and the Planck mean absorption coefficient.

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