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Contrasting turbulence–radiation interaction in supersonic channel and pipe flow

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ABSTRACT

The Large Eddy Simulation (LES) technique is used to explore similarities and differences between turbulence–radiation interaction (TRI) in fully developed supersonic plane channel flow and axisymmetric non-swirling pipe flow, bounded by isothermal black and diffusive walls which are kept at a temperature of 800 K. The comparison between both flows is based on equal friction Mach number, friction Reynolds number, Prandtl number and ratio of specific heats. The Reynolds number is defined with the channel half-width and pipe radius. An explicit filtering scheme based on approximate deconvolution is applied to treat the closure problem of the low-pass filtered compressible Navier–Stokes equations. The working fluid is water vapour and its radiative properties are accounted for using a grey gas model with a Planck mean absorption coefficient varying with temperature. Simulations have been performed for two different optical thicknesses. Results for mean flow quantities, Reynolds stresses and pressure–strain correlations are presented, contrasting radiative effects in both flows and indicating their interaction with curvature effects in the pipe. An analysis of the total enthalpy balance reveals the role of radiative heat transfer, compared to turbulent and mean molecular heat transport.

1. Introduction

Radiative heat transfer plays an important role in many turbulent gaseous combustion systems, besides heat transfer by conduction and convection. But, it also generates noticeable effects in non-reacting shear layers, provided the layers through which the thermal radiative energy travels are large enough for a given absorptivity. The layer thickness also defines a Reynolds number of the flow, which may become a limiting factor in numerical simulations. Thermal radiation is a phenomenon of much longer range than heat transfer by conduction and convection, in general, because photons can travel long distances before they interact with molecules. While a set of partial differential equations (here the compressible Navier–Stokes equations) describe heat conduction and convection mechanisms at high flow speed, the radiative transfer equation (RTE), predicts the directional dependence of the radiative intensity and becomes a single partial differential equation inside absorbing/emitting gases. The most accurate prediction technique for turbulence–radiation interaction is undoubtedly the Direct Numerical Simulation (DNS) of a turbulent flow, the Monte Carlo method for radiative transfer (Wu et al., 2005) and a model for the radiative properties for the medium (Modest, 2003) with an accuracy which is consistent with that of the simulation approach. Unfortunately, such an accurate approach is not feasible at present due to the prohibitive computational requirements even for simple flow configurations where turbulence is inhomogeneous only in one space direction. A good compromise with respect to accuracy and cost is achieved by performing a large-eddy simulation (LES) of the flow field, applying the discrete ordinate method (Modest, 2003; Coelho, 2007) to compute the radiative transfer equation for an absorbing/emitting gas without taking care of possible unresolved emission and absorption effects (Coelho, 2009). Since the radiative properties of gases mostly vary strongly with the frequency or wavenumber of radiation, their detailed account in an LES leads to a further increase of the computational costs which can, however, be circumvented without losing the essential features of TRI, by using a specific grey gas model (Gupta et al., 2009).

The work of Gupta et al. (2009) is one of the several examples of TRI studied in internal flows. The authors use LES to investigate a reacting and non-reacting incompressible turbulent channel flow at a friction Reynolds number of 186 under conditions where composition and temperature do not affect the hydrodynamics (one-way coupling). The radiative transfer equation is solved using a spherical harmonics (P1) method, and radiation properties

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correspond to a fictitious grey gas with a composition- and temperature-dependent Planck-mean absorption coefficient. Amaya et al. (2010) have performed DNS of a reacting turbulent minimal channel flow with and without radiative source terms. The radiative transfer equation is solved using the discrete ordinates method and the radiation model used is the global spectral FS-SNBcK model (Poitou et al., 2009) which forms a compromise between cost and accuracy. Radiation and flow dynamics are directly coupled. Specific features of the flow are internal heat sources to achieve a bulk temperature of 2000 K, a friction Reynolds number of 400, a low optical thickness and isothermal, black walls, kept at a temperature of 1750 K. The working gas is a mixture of seven reacting species typical of many industrial applications: CO, CO_2, H, H_2, H_2O, OH and N_2. As a result of the author's low optical thickness and low-temperature configuration, no noticeable coupling is detected between the radiation term and other terms in the energy balance. In our own contribution (Ghosh et al., 2011) we have investigated supersonic turbulent channel flow with pure water vapour as working fluid and black no-slip surfaces kept at constant temperature of 1000 K. High temperatures are naturally created in the channel core by kinetic energy dissipation at bulk Mach numbers of 1.26 and 2.88. Moderate friction Reynolds numbers were chosen (O(1000)) in order to keep the scale resolution problem tractable. This, however, has led to very low optical thicknesses and weak turbulence–radiation interaction for the realistic SNB-cK radiation model (Liu et al., 2000) due to the small channel heights. To obtain higher optical thicknesses at moderate friction Reynolds numbers and turbulence statistics which are noticeably affected by radiative heat transfer, we have used the grey gas model of Gupta et al. (2009) as well (see Eq. (9)) and have artificially increased Planck's mean absorption coefficient. In the recently published work of Zhang et al. (2013), a DNS of low Mach number turbulent channel flow is performed using an inert gas mixture of carbon dioxide, water vapour and nitrogen as working fluid. The channel walls are isothermal and kept at different temperatures. Effects of gas–gas and gas–wall interactions are taken into account by fully coupling them with the fluid flow. The RTE is solved using a reciprocal Monte Carlo approach (Zhang et al., 2012). The gas radiative properties are determined by means of the correlated-k distribution (CK) model or its weak absorption limit, depending on the pressure condition (Soufiani and Taine, 1997). Results are presented both for effects of turbulence on radiation fields and of radiation on turbulent fields.

Finally, we would like to point out that an extensive overview of present-days knowledge on TRI and its modelling in reactive low Mach number flows has been provided by Coelho (2007). It includes two different aspects: namely the influence of a turbulent flow field on the radiative heat transfer via the density and temperature fields and the effect of radiation on the structure of turbulent flows. While in the past research on TRI has mostly focused on turbulence influencing radiation, relatively little work has been done to improve our understanding of structural changes of turbulence via radiation, an exception being the recent work of Zhang et al. (2013).

It is the aim of this work to focus on the behaviour of the turbulence structure under the influence of thermal radiation in inert compressible fully-developed plane channel and axisymmetric non-swirling pipe flow; especially, to explore similarities and differences between these flows, resulting from their different geometries. The choice of water vapour as working fluid is motivated by the fact that it is one of the principal products of hydrocarbon combustion and has important radiative properties. The paper is organised as follows: The compressible Navier–Stokes equations for a single-component thermally radiating gas are presented in Section 2, together with the radiative transfer equation for an emitting–absorbing non-scattering grey gas. Section 3 discusses the numerical integration of these equations and our LES approach. The flow configurations, physical and numerical parameters are outlined in Section 4. Section 5 is devoted to the discussion of results for mean flow variables and second order turbulence statistics under very similar flow conditions (Reynolds and Mach numbers), but three different conditions regarding radiative heat transfer: (i) no radiation; (ii) weak optical thickness; (iii) moderate optical thickness. Conclusions are drawn in Section 6.

2. Modelling fluid flow and radiative heat transfer

The compressible Navier–Stokes equations for a thermally radiating gas read:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \vec{u}) = 0 \tag{1}$$

$$\frac{\partial \rho \vec{u}}{\partial t} + \nabla.(\rho \vec{u}\vec{u}) + \nabla.(p\underline{\underline{\delta}} - \underline{\underline{\tau}}) = \vec{f} \tag{2}$$

$$\frac{\partial E}{\partial t} + \nabla.(E\vec{u}) + \nabla.(\vec{u}.p\underline{\underline{\delta}} - \vec{u}.\underline{\underline{\tau}} + \vec{q}) = \vec{u}.\vec{f} \tag{3}$$

The set (1)–(3) of coupled differential equations describes the transport of mass, momentum and total energy ($E = \rho(e + 0.5\vec{u}\cdot\vec{u})$). It is supplemented by Newton's viscous stress tensor ($\underline{\underline{\tau}}$), the sum ($\vec{q} = \vec{q}_C + \vec{q}_R$) of heat flux vectors for conduction (C) and radiation (R) and the caloric and thermal equations of state:

$$\underline{\underline{\tau}} = \mu\left(\nabla\vec{u} + (\nabla\vec{u})^T\right) + (\kappa - 2/3\mu)(\nabla.\vec{u})\underline{\underline{\delta}} \tag{4}$$

$$\vec{q} = -\lambda\nabla T + \vec{q_R} \tag{5}$$

$$de = C_v dT, \quad p = \rho R_G T \tag{6}$$

In Eqs. (1)–(6) $\rho, \vec{u}, p, T, e$ denote density, velocity, pressure, temperature, and internal energy. $\underline{\underline{\delta}}$ is the Kronecker delta and R_G is the gas constant per unit mass. Its value for water vapour is 461.5 J/(kg K). The dynamic viscosity is proportional to the nth power of the temperature, $\mu \propto T^n$ with $n = 0.7$. Specific heats are assumed to be constant at a ratio of $\gamma = C_p/C_v = 1.27$ for water vapour. The Prandtl number $Pr = C_p\mu/\lambda = 0.76$ is kept constant as well. $\vec{f}$ represents a homogeneous body force which is used to drive fully-developed channel/pipe flow and to replace the mean pressure gradient. The radiative source term, $\nabla.\vec{q_R}$, in the energy equation is obtained by integrating the radiative transfer equation (RTE) over all wavenumbers and directions in which radiation propagates. For an emitting–absorbing non-scattering grey gas, the governing equation for the radiative intensity I reads (Modest, 2003):

$$\vec{s}.\nabla I = \kappa I_b - \kappa I \tag{7}$$

I depends on the direction $\vec{s}$ in which the radiative energy propagates and on the location in space, $\vec{x}$. Its time-dependency is neglected because the speed of light is much larger than any flow velocity. κ, I_b denote the (frequency-integrated or) total absorption coefficient and black body radiative intensity. The first term on the right-hand-side of Eq. (7) describes the gain of radiative intensity by emission and the second the loss by absorption. The radiative source term appearing in the energy equation is obtained from (7) through integration over the solid angle Ω:

$$\nabla.\vec{q_R} = 4\pi\kappa I_b - \kappa\int_{4\pi} I d\Omega = \underbrace{4\kappa_P\sigma T^4}_{emission} - \underbrace{\kappa\int_{4\pi} I d\Omega}_{absorption} \tag{8}$$

κ_P denotes Planck's absorption coefficient. σ is the Stefan–Boltzmann constant. The refractive index is assumed constant, equal to one and hence does not appear in (8). Following Gupta et al. (2009) we adopt the Planck mean absorption coefficient in the form:

$$\kappa_P = C_k\left[c_o + c_1(A/T) + c_2(A/T)^2 + c_3(A/T)^3 + c_4(A/T)^4 + c_5(A/T)^5\right] \tag{9}$$