DIRECT NUMERICAL SIMULATION OF A TURBULENT CHANNEL FLOW COUPLED TO RADIATIVE TRANSFER

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Summary Direct numerical simulation of a turbulent CO_2-H_2O-N_2 mixture flow in a two-dimensional channel is performed. It is coupled with a reciprocity Monte Carlo method to compute velocity and temperature profiles when radiation is taken into account. The two walls of the channel are isothermal at 950K and 1150K respectively. The bulk Reynolds number is 6,000. The radiation affects significantly the mean temperature profile and wall heat flux. In our case, the classical wall law is no longer valid when the radiation is considered.

Introduction

Radiation plays an important role in many industry applications involving, in particular, gases at high pressure, high temperature. Boundary layers determine the level of convective heat flux, it is then meaningful to study how radiation modifies the temperature field in the near wall region. Classical wall laws are derived for zero pressure gradient incompressible flows. In practical systems, other physical effects have to be considered such as Prandtl number effect[1], compressibility[2], streamwise pressure gradient[3], chemical reaction[4] and radiation [5, 6, 7]. The impact of radiation on the boundary layer fields depends on the conditions: it was found to be small by Amaya *et al.* [5] and significant in other studies [6, 7]. This paper focuses on radiation effects on the temperature field and on the wall conductive flux in a turbulent channel flow.

Problem description

A turbulent non-reacting CO_2-H_2O-N_2 gas mixture flows through a two-dimensional channel at atmospheric pressure. The gas molar composition is $X_{CO_2} = 0.116$, $X_{N_2} = 0.729$ and $X_{H_2O} = 0.155$. The two walls are isothermal at $T_{w1} = 950$K and $T_{w2} = 1150$K. In the homogeneous streamwise(x) and spanwise(z) directions, periodic boundary conditions are applied. Re_b based on the bulk properties and half-height of the channel h, along y, is equal to 6,000. Friction Reynolds numbers $Re_{\tau 1}$ and $Re_{\tau 2}$, based on friction velocity, are 374 and 297 respectively. The domain size is ($2\pi h, 2h, \pi h$), and h is 0.1m. The grid is composed of $110 \times 137 \times 110$ cells. The mesh size in wall units varies from $\Delta y^+ = 0.8$ at the wall to 8 at the centerline, while Δx^+ belongs to the range [16.9, 21.3] and Δz^+ to [8.4, 10.6]. Cases with and without radiation are both considered. With radiation, the emissivity of the walls is set to 0.1.

The flow simulation is a direct numerical simulation performed with the low-Mach number code YALES2 [9]. It solves the variable-density Navier-Stokes equations under the low-Mach number assumption (here, Ma = 0.012). The radiation computation is carried out by an Optimized Emission-based Reciprocity Method of Monte Carlo (OERM) [10] and gas radiative properties are modeled in a correlated manner by a CK model. The grid used by the radiation model is three times coarser in x direction and two times in y and z directions than the grid used by the low-Mach solver.

Results

Fig 1(a) shows that the mean velocity profile is not affected by radiation in this case where density variations are small. However, when radiation is considered, the mean temperature profile becomes more uniform in the core region of the channel and consequently, a stronger gradient appears near the walls. Indeed, radiation transfers energy at long range from the high temperature region to the cold one.

Fig 1(b) shows the profile of T^+, the normalized temperature based on friction velocity and conductive wall heat flux. Without radiation, the mean temperature profiles of the two sides collapse and agree with the wall law: $T^+ = 2.78\, \mathrm{In} y^+ + 2.09$[8]. However, with radiation, the mean temperature profile significantly changes. The wall law is then not suitable anymore for the temperature profile when radiation effects are noticeable.

The enthalpy conservation equation writes

$$\frac{d(\overline{\rho}\widetilde{v''h''})}{dy} = -\frac{d\left(\overline{q_y}\right)}{dy} - \frac{d\left(\overline{q_r}\right)}{dy} \tag{1}$$

where, in a Low Mach number assumption, the pressure and viscous terms have been neglected. The three remaining contributions are: the turbulent heat flux, $\overline{\rho}\widetilde{v''h''}$, the Fourier flux, $\overline{q_y}$, and the radiative flux, $\overline{q_r}$.

Fig. 1(c) compares the profiles of these three contributions with and without radiation. Without radiation, the Fourier flux is important near the wall and its absolute value decreases rapidly towards the channel center. The total heat flux, sum of Fourier flux and turbulent convective flux, is constant along y.

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Table 1. wall heat flux(the unit is W/m^2)

	Fourier flux (cold side)	Fourier flux (hot side)	Radiative flux (cold side)	Radiative flux (hot side)	Total flux (cold side)	Total flux (hot side)
without radiation	-866.4	-868.6	–	–	-866.4	-868.6
with radiation	-1266.3	-1203.7	-724.1	-800.9	-1990.4	-2004.6

With radiation, the wall-wall radiation flux has been removed from the radiative flux since only gas-gas and gas-wall radiation plays a role in the coupling. The radiative flux reaches its peak value in the channel center while the absolute turbulent convective flux value decreases. However, the sum of the three contributions is constant along y (not shown here). Indeed, the radiation decreases the turbulent fluctuation in the center part due to the temperature homogenization.
Tab. 1 compares the different fluxes contributions (only gas-gas and gas-wall contributions for radiation). It shows that radiation strongly increases Fourier fluxes at both walls. Indeed, radiation is a transfer which homogenize the temperature profile in the core of the channel and steepens the gradients at the walls. These effects appear here because the gas-gas and gas-wall radiative fluxes and the Fourier fluxes are of the same order of magnitude in the vicinity of the wall.

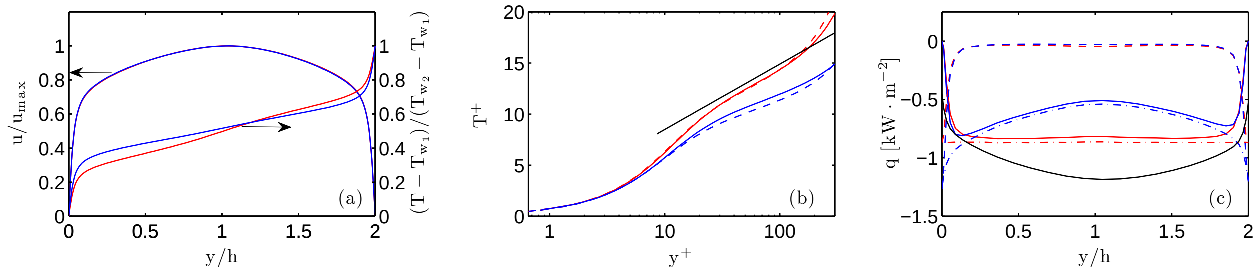

Figure 1. (a) Mean profile of streamwise velocity and temperature (——: without radiation; —— : with radiation.); (b) Mean profile of temperature in wall units (——: cold side without radiation; – – –: hot side without radiation; ——: cold side with radiation; – – –: hot side with radiation; ——: wall law [8]); (c) Mean heat fluxes (——: turbulent convective flux (without radiation); – – –: Fourier flux (without radiation); -· -: total heat flux (without radiation), $-\lambda\frac{dT}{dy}+\overline{\rho}\widetilde{v''h''}$; ——: turbulent convective flux (with radiation); – – – : Fourier flux (with radiation); -· - : $-\lambda\frac{dT}{dy}+\overline{\rho}\widetilde{v''h''}$; ——: radiative flux (gas-gas and gas-wall), q_r;

Conclusions

This paper presents the mean flow field results of a turbulent channel flow with or without radiation using direct numerical simulation of turbulence and a Monte-Carlo radiative transfer model . With radiation, the mean temperature profile is strongly modified and the classical wall law is no longer valid. Radiation homogenizes the mean temperature profile in the channel center region and steepens the wall Fourier flux. Indeed in our conditions, Fourier flux and the gas-gas and gas-wall radiation fluxes are of the same order of magnitude, which improves the coupling.

References

[1] Kader B. A.: Temperature and concentration profiles in fully turbulent boundary layers. *Int. J. Heat Mass Transfer* **24(9)**:1541-1544,1981.
[2] Coleman G. N. , Kim J. and Moser R. D.:A numerical study of turbulent supersonic isothermal-wall channel flow. *J. Fluid Mechanics* **305**:159-183,1995.
[3] Huang P. G. and Bradshaw P. : Law of the wall for turbulent flows in pressure gradients. *AIAA J.* **33(4)**:624-632,1995.
[4] Cabrit O., Nicoud F.: Direct simulations for wall modeling of multicomponent reacting compressible turbulent flows. *Phys. Fluids* **21**:055108,2009.
[5] Amaya J., Cabrit O., Poitou D., Cuenot B. and El Hafi M.: Unsteady coupling of Navier-Stokes and radiative heat transfer solvers applied to an anisothermal multicomponent turbulent channel flow. *J. Quant. Spectrosc. Radiat. Transf.* **111(2)**:295-301,2010.
[6] Soufiani A. and Taine J. : Application of statistical narrow-band model to coupled radiation and convection at high temperature . *Int. J. Heat Mass Transfer* **30**:437-447, 1987.
[7] Ghosh S. and Friedrich R. and Pfitzner M. and Stemmer C. H. R. and Cuenot B. and El Hafi, M.: Effects of radiative heat transfer on the structure of turbulent supersonic channel flow. *J. Fluid Mech.* **677**:417-444, 2011.
[8] Dailey L. D., Meng N., and Pletcher R. H. : Large Eddy Simulation of Constant Heat Flux Turbulent Channel Flow With Property Variations: Quasi-Developed Model and Mean Flow Results . *J. Heat Transfer* **125**:27-38,2003.
[9] Moureau V., Domingo P. and Vervisch L.: Design of a massively parallel CFD code for complex geometries. *C. R. Mecanique* **339**:141-148, 2011.
[10] Zhang Y.F., Gicquel O., Taine J.: Optimized Emission-based Reciprocity Monte Carlo Method for fast computation in complex systems. Submitted to *Int. J. Heat Mass Transfer*