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WALL-MODELED LES WITH A NEW WALL MODEL ACCOUNTING FOR RADIATION EFFECTS

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ABSTRACT. In order to consider the effects of radiation on the temperature profile in the near wall region of a turbulent channel flow, a new wall model is proposed where turbulent boundary layer equations are resolved on an embedded grid. The obtained wall-modeled LES is coupled with a Monte-Carlo method for a computation of a turbulent channel flow where radiation is taken into account. The results of this wall-modeled LES are in good agreement with DNS results.

INTRODUCTION

In order to alleviate the high resolution requirement of the near wall layer, instead of using fully resolved Large Eddy Simulation (LES), wall-modeled LES has been widely applied for wall-bounded flows in engineering application. In wall-modeled LES, the no-slip wall boundary condition is replaced by an approximated condition. In order to realize this approximated condition, Balaras et al. [1] developed a Two-Layer Model (TLM) in which turbulent boundary layer equations are resolved on an embedded grid. This model has been successfully extended to temperature field by Benarafa et al. [2]. However, up to now, no wall model has accounted for radiation effects, although radiation strongly modifies the temperature fields in many applications. Recent results from Direct Numerical Simulations (DNS) of a turbulent channel flow have shown that the temperature profile and the corresponding wall laws and wall conductive fluxes can be significantly modified by radiation [3]. Hence, the objective of this study is to propose a new wall model for LES by taking into account this effect.

NUMERICAL MODEL AND STUDIED CONFIGURATION

In the wall-modeled LES, the unresolved wall inner layer is modeled by solving balance equations of a 1-D equilibrium flow. The low-Mach code YALES2 [4] is used for LES. The numerical scheme is 4th-order in space and time. The Sigma model [5] is retained for Sub-Grid Scale (SGS) modeling with the SGS Prandtl number $\mathrm{Pr}_{\mathrm{SGS}}$ set to 0.9. For radiation, an Optimized Emission-based Reciprocal Monte-Carlo method (OERM) [6] is used to calculate the radiative power at all the LES grid points.

The unresolved inner layer $[0,\, h_w]$ of the flow field is treated as a thin equilibrium boundary

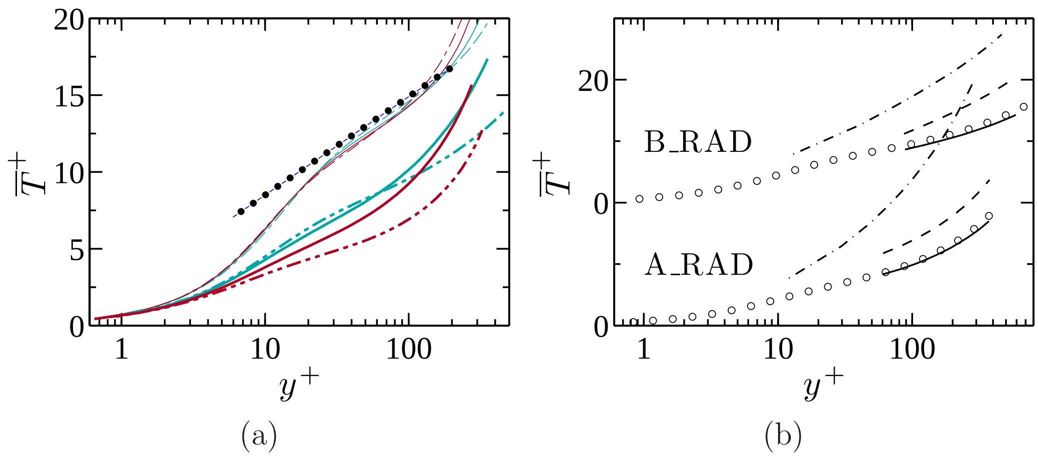

Figure 1: (a) $\overline{T}^+$ profile of A, B, A_RAD and B_RAD from DNS [3] (-●-: Wall function of Ref. [10]; —: A; **—**: A_RAD; – - – : B **–··–** : B_RAD; color— : Cold side; color — : Hot side); (b) $\overline{T}^+$ profile on the cold side of A_RAD and B_RAD from LES (∘ : DNS datas from [3]; **- · -** : without wall model; **– –** : wall model without radiation term; **—**: proposed wall model).

layer, leading to the following equations

$$\frac{d}{dy}[(\langle\mu\rangle + \langle\mu_t\rangle)\frac{d\{u_{||}\}}{dy}] = 0; \qquad \frac{d}{dy}[\langle c_p\rangle(\frac{\langle\mu\rangle}{\mathrm{Pr}} + \frac{\langle\mu_t\rangle}{\mathrm{Pr_t}})\frac{d\{T\}}{dy}] + \langle P^R\rangle = 0, \tag{1}$$

where the angled brackets $\langle\cdot\rangle$ and curly brackets $\{\cdot\}$ denote Reynolds averaged and Favre averaged values respectively. $u_{||}$ is the tangential velocity parallel to the wall and y is the distance to the wall. The turbulent viscosity μ_t is calculated by using a mixing-length model [7] and the turbulent Prandtl number $\mathrm{Pr_t}$ is given by an algebraic formula [8]. The radiative power per unit volume P^R is analytically obtained from a 1D radiation model which uses the intensity field obtained from the Monte Carlo solver at any boundary grid point of abscissa h_w.

Two turbulent channel flow cases from [3], with a bulk Reynolds number 5800 and high pressure 40atm, are used in this study. The medium is composed of a non-reacting CO_2-H_2O-N_2 gas mixture. The two cases without radiation are named A and B. The temperature of the two walls $T_{\mathrm{w},1}$ and $T_{\mathrm{w},2}$ for case A is 950K and 1150K respectively while for case B, it is 950K and 2050K. The corresponding cases with radiation are named A_RAD and B_RAD respectively. In these cases, wall emissivities are set to 0.8 and the gas radiative properties are modeled by using the weak absorption limit of CK model[9]. The LES grid consists of $36 \times 36 \times 36$ points.

RESULTS

In order to demonstrate the effect of radiation on the temperature field, the DNS results from ref. [3] are presented in Figure 1 (a). It is shown that the temperature profile T^+ normalized in wall units is significantly decreased by radiation and the standard wall law is no longer suitable for the cases with radiation.

Figure 1 (b) also compares the LES results with DNS results for the two cases with radiation. Results of LES without wall model or with a wall model in which no radiative power term is considered (in eq. 1, $\langle P^R\rangle$ is set to zero). It is observed that, if no radiation is considered in the wall model, the results of the wall-modeled LES differ greatly from DNS results (fig. 1). This is due to the important radiation effect in these cases with radiation. On the other hand, results from the LES with the proposed model are in very good agreement with DNS data.

CONCLUSION

A new wall model for LES is proposed by resolving the thin equilibrium turbulent boundary layer equations with the consideration of radiative power in the energy equation. This new wall model is coupled with LES and Monte-Carlo solver for the simulation of several turbulent channel flow cases where radiation has an important effect. For the cases with radiation, the wall-modeled LES with the proposed wall model predicts the temperature profile with a good agreement with DNS results. However, a great deviation exists between the DNS results and those from LES without wall model or wall-resolved LES with a wall model in which no radiation is considered.

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