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A wall model for LES accounting for radiation effects

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ABSTRACT

In several conditions, radiation can modify the temperature law in turbulent boundary layers. In order to predict such an effect and the corresponding change in conductive heat flux at the wall, a new wall model for large-eddy simulation (LES) is proposed. The wall model describes the inner boundary layer which cannot be resolved by the LES. The radiative power source term is calculated from an analytical expression of the intensity field within the inner layer. In the outer layer, wall stress and conductive heat flux predicted by the wall model are fed back to the large-eddy simulation which is coupled to a reciprocal Monte-Carlo method to account for radiation.

Several mixing-length models and turbulent Prandtl number formula are investigated. Then, the level of accuracy of the discretized radiation analytical model is investigated. Finally, fully coupled results are compared with Direct Numerical Simulation/Monte-Carlo results of turbulent channel flows at different Reynolds number, wall temperature and pressure conditions. The proposed wall model greatly improves the accuracy of the predicted temperature profiles and wall conductive heat fluxes compared to approaches without radiation accounted for in the inner layer.

1. Introduction

Fully resolved Large Eddy Simulation (LES) of the inner layer of a wall-bounded turbulent flow requires highly resolved grids since the integral length scale becomes of the same order of magnitude as viscous scales in the close vicinity of the wall. The computational cost is then proportional to $Re^{2.4}$[1]. Hence, fully resolved LES is impracticable for wall-bounded flows at high Reynolds number, encountered in most of engineering applications, due to the prohibitive cost. Several kinds of approaches are commonly used in order to alleviate these difficulties: A wall model prescribes the correct wall shear stress to the LES that is too poorly resolved close to the wall to estimate it accurately.

In hybrid RANS/LES, the simulation is switched from RANS in the inner layer to LES in the outer layer by the modification of the length scales [2,3] or the use of a blending function [4,5] in the turbulent transport model. In other wall models for LES, the wall stress is estimated by using an algebraic wall function or by locally solving a simplified RANS equation. These approaches correspond to equilibrium-stress model and Two-Layer Model (TLM), respectively.

The equilibrium-stress model has been firstly proposed by Deardroff [6]. It has then been successfully applied to turbulent channel flows and annuli flows [7]. However, this model is restricted to simple flows, since it implies the existence of a logarithmic layer. In order to widen its use to more complex flows, the original equilibrium model has been modified by considering inclination of the elongated structure in near wall region [8], pressure gradient [9,10], buoyancy [11] or chemistry [12].

In two-layer models, turbulent boundary layer equations are resolved on a local embedded grid [13]. This approach has been extensively applied and assessed in different configurations [14–16]. Moreover, since all wall modeled LES unavoidably suffers from the numerical and sub-grid error at the first grid point close to a wall [14,17], an effective strategy has recently been proposed by Kawai et al. [18] to increase the accuracy of the information transmitted from LES in the outer layer to the inner thin turbulent boundary layer equations.

A more detailed description of wall models for velocity is given in Refs. [19,1,14]. In order to deal with turbulent heat transfer and predict wall heat fluxes accurately, these wall models have to be extended to describe the thermal boundary layer as in [20,21]. To the best of our knowledge, no wall model for LES has accounted for radiation effects, although radiation strongly modifies the temperature field in many applications, particularly in combustion processes at high pressure [22–24]. It has been recently shown [25] in coupled DNS-Monte Carlo simulations that radiation can

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Nomenclature

Roman symbols

c_p	thermal capacity at constant pressure [J kg^{-1} K^{-1}]
e	optical thickness [–]
h	enthalpy per unit mass [J kg^{-1}]
I	radiative intensity [W m^{-2} sr^{-1}]
L	length [m]
p	pressure [Pa]
Pr	Prandtl number [–]
P	power per unit volume [W m^{-3}]
q	heat flux [W m^{-2}]
Re	Reynolds number [–]
S_i	momentum source term [N m^{-3}]
t	time [s]
T	temperature [K]
u	streamwise velocity component [m s^{-1}]
u_i,u_j	velocity vector [m s^{-1}]
X,Y,Z	Cartesian coordinates [m]
x_i	coordinate vector (tensorial) [m]
y	distance to a wall [m].

Greek symbols

δ	channel half-width [m]
δ_{ij}	Kronecker delta operator [–]
κ	spectral absorption coefficient [m^{-1}]
λ	thermal conductivity [W K^{-1} m^{-1}].
ρ	gas mass density [kg m^{-3}]
τ_{ij}	viscous shear stress tensor [N m^{-2}]
Ω	solid angle [sr]
ν	radiation wave number [cm^{-1}] or kinematic viscosity [m^2/s]
θ	polar angle [sr]
μ	dynamic viscosity [kg s^{-1} m^{-1}] or cosine of polar angle [–]

Superscripts

$\bar{\cdot}$	filtered quantities
$\tilde{\cdot}$	mass-weighted filtered quantities
$''$	mass-weighted fluctuating quantities
SGS	subgrid-scale quantities
a	absorbed quantities
e	emitted quantities
0	equilibrium quantities
+	wall-scaled quantities or quantity in positive y direction
-	Quantities in negative y direction

Subscripts

b	bulk quantities
c , h	refer to the cold wall, respectively to the hot wall
cd	conductive quantities
R	radiative quantities
t	turbulent quantities
w	wall quantities
y_w	quantities at position $y = y_w$ of the 1D model
τ	friction quantities
ν	spectral quantities
0	quantities at position $y = 0$ of the 1D model

Brackets

$\langle \cdot \rangle$	Reynolds averaged quantity in the 1D model
$\{ \cdot \}$	favre averaged quantity in the 1D model

Abbreviations

DNS	Direct Numerical Simulation
LES	Large Eddy Simulation
RANS	Reynolds-averaged numerical simulations
OERM	optimized emission reciprocity method
TLM	two-layer model
SGS	sub-grid scale
rms	root mean square

significantly influence the temperature wall-law and the corresponding wall conductive heat flux. The temperature law is very different from the usual logarithmic law for strong radiation effects and has been observed to differ significantly under different radiative conditions. It is therefore unrealistic to hope for a general algebraic wall-law to account for these effects and a two-layer approach is then chosen. Besides, in order to predict the radiative field outside of the inner boundary layer, a reciprocal Monte-Carlo method is considered. The method is accurate and can be applied to complex geometries so that the proposed wall-model and its coupling with LES and the Monte-Carlo method remain general.

The objective of this study is to account for radiation effects in the inner layer wall model to accurately predict wall stress and heat flux. Here, a two-layer model is retained where, in the outer layer, LES is coupled to a radiation Monte Carlo method as in Ref. [25]. Coupled DNS-Monte Carlo results of Ref. [25] are considered to validate the proposed LES wall model. The fluid and radiation models in both layers are detailed in Section 2, followed by a description of coupling between the inner and outer layers. Separate validations of the different model components are presented in Section 3. Finally, in Section 4, fully coupled results assess the model accuracy.

2. Wall-modeled LES coupled to radiation

In all fluid simulations, LES is here carried out in the outer layer and the boundary inner layer is modeled by solving 1D balance equations. For radiation, a reciprocal Monte Carlo approach is implemented to estimate the radiative power at all LES grid points and an analytical radiative 1D model is developed for the inner layer. For both radiation and fluid models, a particular care is brought to the boundary conditions, especially between the inner and outer layers.

2.1. Fluid model

As shown in Fig. 1, an embedded grid is used in the inner layer. The inner layer model uses the velocity $\tilde{u}_{y_w}$ and temperature $\tilde{T}_{y_w}$ values computed by the LES model at a particular point characterized by the wall distance y_w. The wall stress τ_w and conductive heat flux q_w^{cd} computed by the inner layer model are then sent back to the LES solver.

2.1.1. Inner layer fluid model

As explained in Ref. [1], filtered equations in the inner layer are similar to averaged Navier–Stokes equations. Then, treating the unresolved inner layer $[0, y_w]$ as a thin equilibrium boundary layer [15,14] leads to the following equations

$$\frac{\mathrm{d}}{\mathrm{d}y}\left((\langle\mu\rangle + \langle\mu_t\rangle)\frac{\mathrm{d}\{u_\parallel\}}{\mathrm{d}y}\right) = 0;$$
$$\frac{\mathrm{d}}{\mathrm{d}y}\left(\langle c_p\rangle\left(\frac{\langle\mu\rangle}{\mathrm{Pr}} + \frac{\langle\mu_t\rangle}{\mathrm{Pr_t}}\right)\frac{\mathrm{d}\{T\}}{\mathrm{d}y}\right) + \langle P^R\rangle = 0, \quad (1)$$