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Turbulent forced convective flow in an anisothermal channel

Syed Mohd Yahya [a,*], Syed Fahad Anwer [b], Sanjeev Sanghi [a]

[a] Department of Applied Mechanics, Indian Institute of Technology Delhi 110016, India
[b] Department of Mechanical Engineering, Aligarh Muslim University, Aligarh 202002, India

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ABSTRACT

The influence of variable viscosity effects on momentum and heat transfer of a non-isothermal turbulent forced convective flow is studied using thermal large-eddy simulation (LES). LES of bi-periodic channel flow with significant heat transfer at a low Mach number was performed to study the modulation in the near-wall turbulence structure due to anisotropic viscosity. The temperature ratio ($R_\theta = T_{hot}/T_{cold}$) is varied from 1.01 to 5 to study the isolated effect of variable viscosity with (T_{hot}) and (T_{cold}) as a wall temperature. It is shown that average and turbulent fields undergo significant changes in a broad range of Reynolds number, compared to isothermal flow with constant viscosity, we observe enhanced turbulence on the cold side of the channel, characterized by locally lower viscosity whereas a decrease of turbulent kinetic energy is found at the hot wall. The turbulent structures via *H* criteria of high vorticity shows very short and densely populated vortices near cold wall whereas long streaky structure or large elongated vortices at the hot wall. *Q* invariant totally eradicate all the streaky structure at the hot wall as a consequence of relaminarization. To further clarify this issue spectral study is conducted that reveals complete suppression of turbulence at the hot side of the channel at large temperature ratio because no inertial zone (i.e. index of Kolmogorov scaling law is zero) is obtained on the spectra in these region.

1. Introduction

The role of turbulent flows characterized by large temperature gradients and high heat transfer rates is of great importance in engineering. Many industrial application have large thermal flux accross the near wall region of the flow (e.g. heat exchangers, combustion chamber, nuclear reactor and solar receivers etc.). In these processes, thermal and viscous properties of fluid are critical design parameters that vary with temperature. Also there is a strong interaction between energy and momentum equations. This anisotropic property and strong coupling between thermal and kinetic field results in asymmetric velocity profiles and changes important flow quantities such as the Nusselt number and friction factor. The thermal kinetic interaction due to large temperature gradient in case of supersonic compressible flow is studied by many workers [1–4], however in case of low speed flow we have fewer studies. In literature there is no reference data available for low Mach number flow aimed at evolving variable viscosity and dilatational effects due to temperature stratification. The present work describe the role of viscosity on the flow field keeping all other thermo-fluid properties to be constant. Among analytical and numerical studies dealing with temperature-dependent viscosity problems, a large majority was devoted to the analysis of laminar heat convection. Shin et al. [5] developed a finite-volume algorithm to study laminar heat transfer in a rectangular duct. The authors focused on the numerical prediction of friction factor and Nusselt number when constant flux boundary conditions are enforced at the top and bottom walls, and imposed temperature conditions are prescribed at the sidewalls. Results revealed an increase in the Nusselt number with respect to the case of constant viscosity. Pinarbasi et al. [6] studied the influence produced by variations in both thermal conductivity and viscosity of a Newtonian fluid for the case of laminar Poiseuille flow in a two-dimensional channel with constant-temperature boundary conditions. Non-uniform viscosity and thermal conductivity affected the temperature field, while very scarce effects were observed on the velocity field. Nicoud [7] perform first DNS study of channel flow with variable flow properties with temperature ratio from 1.01 to 4 and report only about asymmetric behaviour of flow field. Lessani [8] studied the effect of large temperature gradient on the physics of channel taking air as a fluid but restrict themselve to a single Reynolds number $Re_\tau = 180$. Lessani perform LES to study the spatio-temporal dynamics taking both thermal conductivity and viscosity to be varying. However it lacks in physical interpretation and higher order statistics. Serra

* Corresponding author.
E-mail address: yahya_syed@rediffmail.com (S.M. Yahya).

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et al. [9] performed simulation at Reynolds numbers $Re_\tau = 180$ and $Re_\tau = 395$ to analyse the combined effect of thermal conductivity and viscosity of air on the flow physics. They try to discuss some issues related to subgrid models and mechanism responsible for asymmetric behaviour but did not point out exact role of individual property. Recently Toutant and Bataille [10] perform DNS of channel flow submitted to high temperature gradient with air as a fluid considering thermal conductivity and viscosity to be varying. Their study is based on mesh refining having low temperature gradient across the wall with mere focus on physical perspective.

The objective of the present work is to perform Thermal Large Eddy Simulation (TLES) in particular range of Reynolds number to investigate the behaviour of turbulence when the fluid viscosity varies significantly with temperature while conductivity and specific heats are assumed constant in the absence of volume force (neglecting gravity). Simulations are based on TLES with momentum and energy equations coupled by the explicit dependence of viscosity through Sutherlands law.

With reference to the schematics of Fig. 1, we consider a weakly compressible and Newtonian turbulent flow of air in a plane channel with differentially heated walls: the hot wall is kept at temperature T_{hot} while the cold wall is kept at temperature T_{cold}. The flow is driven by a constant pressure gradient along the streamwise x direction. The channel walls are normal to z-direction and are at constant temperature. The no-slip velocity condition is applied for the fluid velocity at walls, the boundaries of domain normal to x and y directions are periodic. The typical channel dimensions considered are $4\pi\delta \times 4\pi\delta/3 \times 2\delta$ with $\delta = 1$. Different values of the friction Reynolds number, Re_τ are considered while the Prandtl number is kept constant ($Pr = 0.71$). The range of Re_τ was chosen taking into account that the viscous term exhibits a $(Re_\tau)^{-1}$ scaling in our governing equation and viscosity effects vanish at very large Reynolds number. Therefore, we selected four values of Re_τ in the low/intermediate turbulent range (150, 180, 245, 460) to explore these effects in detail.

2. Governing equations and numerical modelling

In low-speed turbulent channel flow applications, the low Mach-number, variable-density approximation of the Navier–-Stokes equations is a good basis for simulation, as it supports large density variations while eliminating acoustic waves. This eliminates the need for extremely small time steps guided by the acoustic velocity. This means that the arising velocities are much smaller than the speed of sound, so that density variations due to pressure variations can be neglected. Firstly the low Mach-number approximation of the Navier–Stokes equations is obtained as the low Mach-number asymptotic limit of the compressible Navier–-Stokes equations. Details of the derivation of these equations can be found in Refs. [11–14]. Favre averaged and filtered equations using implicit filter to obtained governing equation for channel flow

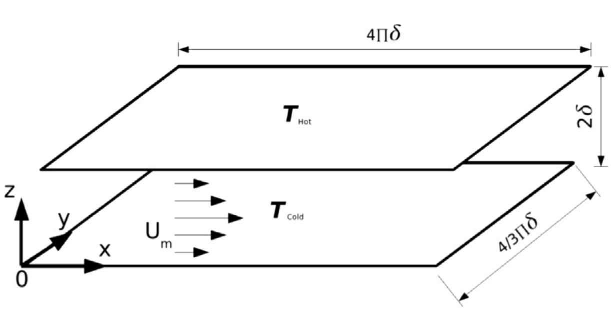

Fig. 1. Schematic of channel flow configuration.

configuration. The filtering operation can be written in terms of convolution integral as,

$$\bar{f}(x) = \int_D G(x - x')f(x')\mathrm{d}x' \tag{1}$$

An f turbulent variable is splitted into an $\tilde{f}$ large component and f' subgrid component. Note that $\tilde{}$ corresponds to the Favre average operator where Favre average is defined by (Eq. (2)).

$$\tilde{f} = \frac{\overline{\rho f}}{\bar{\rho}} \tag{2}$$

The Favre filtered low Mach equation for TLES are given below [14]

$$\frac{\partial \rho}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_j}{\partial x_j} = 0 \tag{3}$$

$$\frac{\partial(\bar{\rho}\tilde{u}_i)}{\partial t} + \frac{\partial(\bar{\rho}\tilde{u}_i\tilde{u}_j)}{\partial x_j} = \frac{-\partial\bar{P}}{\partial x_i} + \frac{\partial(\tilde{\tau}_{ij} - \sigma_{ij})}{\partial x_j} + F\delta_{i1} \tag{4}$$

$$C_p\left[\frac{\partial\left(\bar{\rho}\tilde{T}\right)}{\partial t} + \frac{\partial\left(\bar{\rho}\tilde{u}_j\tilde{T}\right)}{\partial x_j}\right] = \Gamma\left(\frac{\mathrm{d}\overline{P_0}}{\mathrm{d}t}\right) + \frac{\partial\left((\tilde{\kappa})\frac{\partial\tilde{T}}{\partial x_j}\right)}{\partial x_j} - C_p\frac{\partial\bar{\rho}(H_j)}{\partial x_j} \tag{5}$$

$$\overline{P_0} = \bar{\rho}\tilde{T} \tag{6}$$

$$\frac{\partial\overline{P}_0}{\partial x_i} = 0 \tag{7}$$

where u_i is the ith component of the velocity vector, P and P_0 is the fluctuating kinematic and thermodynamic pressure respectively, T is temperature, while F represents the constant streamwise pressure gradient that drives the flow. Here, $\Gamma = \gamma/(\gamma - 1)$, where γ is the specific heat ratio. All the variables have been normalized using the reference state ρ^{ref}, u^{ref}, T^{ref}, $C_p^{\text{ref}} = C_p(T^{\text{ref}})$, $\mu^{\text{ref}} = \mu(T^{\text{ref}})$, $\kappa^{\text{ref}} = \kappa(T^{\text{ref}})$. Also, Reynolds number and Prandtl number are defined as $Re = \rho^{\text{ref}}u^{\text{ref}}L^{\text{ref}}/\mu^{\text{ref}}$ and $Pr = \mu^{\text{ref}}C_p^{\text{ref}}/\kappa^{\text{ref}}$ respectively. Further, as our system is closed, P_o may vary in time but the total mass (M_o) of the system remains constant hence

$$P_o = \frac{M_o}{\int_V \frac{\mathrm{d}V}{T}} \tag{8}$$

Molecular viscosity is calculated with the help of Sutherland law as given below:

$$\frac{\mu(T)}{\mu_{\text{ref}}} = \left(\frac{T}{T_{\text{ref}}}\right)^{\frac{3}{2}}\left(\frac{T_{\text{ref}} + 110.4}{T + 110.4}\right) \tag{9}$$

The balance equation expressing the fluid viscosity are written as

$$\mu(T) = \mu_{\text{ref}} + \mu_\nu(T) \tag{10}$$

where μ_{ref} is the viscosity at reference temperature $T_{\text{ref}} = (T_h + T_c)/2$ and $\mu_\nu(T)$ is the local deviation from Ref. μ_{ref}. Other thermophysical properties like specific heat C_p and thermal conductivity 'κ' were assumed to be constant. This assumption is made primarily because our study focuses on forced-convection heat transfer in zero-