Effects of Strong Temperature Gradient on a Compressible Turbulent Channel Flow

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Abstract

A direct numerical simulation of compressible turbulent channel flow at low Mach number (Ma = 0.3) subject to strong temperature gradient is conducted. The wall temperature ratios which are defined by a temperature on the upper wall ($T_H$) divided by that on the lower one ($T_L$), are set to 2 and 3.

The streamwise, wall-normal and spanwise coordinates are represented by $x$, $y$ and $z$, respectively and the velocity components are $u$, $v$ and $w$ in the similar order. The computational domain is $2.5\pi h \times 2h \times \pi h$ (in $x$, $y$, $z$) with $96 \times 128 \times 96$ grid points. Fully compressible Navier-Stokes equations are discretized by the sixth-order compact finite difference scheme in $x$ and $z$ directions. For $y$ direction, the second-order central finite difference scheme is applied. No numerical diffusion scheme such as upwinding or filtering is used. The working fluid is driven by a constant mass flow rate condition. Time integration is performed by the third-order Runge-Kutta scheme.

Fig. 1 shows the vortical structures and temperature distribution in the case of $T_H/T_L = 2$. The vortical structures are tilted to the wall and coherently distributed on the low temperature side. This appearance is similar to that of the incompressible flow. On the other hand, vortex motion is significantly suppressed on the high temperature side. This feature is attributed to the laminarizing effect over the high temperature wall which comes from a decrease of density and increase of viscosity.

Turbulence intensities are shown in Fig. 2 with the incompressible channel flow database by Iwamoto et al. (2002) referred to ‘ISK’ in the figure. The peak of $u'$ on the high temperature wall side moves toward the center of channel and both of $v'$ and $w'$ are extensively weakened as increasing the temperature ratio. These characteristics are the common features when flow becomes laminarized. On the other hand, the turbulence intensities on the low temperature wall side are almost similar for all cases and correspond well to those for the incompressible flow.

The other results obtained through this study are summarized as follows:

(1) Compressible and dilatational motions are induced on the low and high temperature wall sides, respectively. As a consequence, the mean vertical flow from high to low temperature wall arises.

(2) The identity of friction coefficient on the compressible channel flow is derived via the procedure proposed by Fukagata et al. (2002). Viscous variance component is enhanced as increasing the temperature ratio on the friction coefficient.

(3) The identity of Nusselt number is also derived. Both of viscous work and diffusion coefficient variance components are not negligible on Nusselt number. Furthermore, it is observed that pressure work attains about 20% of the overall Nusselt number.

(4) The pressure work has a redistributive effect between mean kinetic and internal energies. By means of the analysis of internal energy budget (for instance, Huang et al. (1995)), it is clarified that the energy transfer from mean kinetic energy to internal energy appears on the low temperature side whereas toward the opposite direction on the high temperature side even in the present low Mach number flow.

REFERENCES


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Fig. 1 Vortical structure (white) and temperature distribution (from light gray to gray).

Fig. 2 Turbulence intensities.