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Quasi-direct numerical simulation of forced convection over a backward-facing step: Effect of Prandtl number

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ABSTRACT

Quasi direct numerical simulations (quasi-DNS) of forced heat convection over a backward-facing step are performed to study the turbulent heat transfer of low Prandtl number fluids in complex flow regimes. Reynolds number based on step height and inlet bulk velocity equals 4805. The expansion wall is heating by uniform dimensionless heat flux density. Effects of Prandtl number (Pr = 0.01, 0.025, 0.1, 1.0) on mean temperatures, heat transfer coefficients, heat fluxes, turbulent Prandtl numbers and instantaneous velocity and temperature fluctuations, are compared with each other. For low Prandtl numbers, diffusion effect is prominent, thermal boundary layer is much thicker, Nusselt number is smaller and Stanton number is larger. The maximum heat transfer location moves upstream of the reattachment point for larger Prandtl numbers while it is at the reattachment point for low Prandtl numbers. Wall-normal heat flux decomposition shows the turbulent part is comparable to the molecular one in the recirculation zone even for low Prandtl numbers. Turbulent Prandtl number profiles are irregular in the recirculation zone but in the recovering zone they increase first and then decrease. Their peak values decrease as Prandtl number increases. Near-wall instantaneous fields for streamwise velocity and temperature fluctuations show that the streak structures disappear in the recirculation zone but exist in the recovering zone. These highly-resolved data with heat transfer could serve for the validation and improvement of turbulence heat transfer models for low Prandtl media in future.

1. Introduction

Fluids characterized by low Prandtl numbers such as liquid metals, have gained increasing interest in recent years for their high performance in heat transfer and high boiling point. Liquid sodium and lead-bismuth eutectic have already been used as coolants in fast neutrons nuclear facilities. Concentrated solar power technology also plans to take liquid metals as heat transfer medium (Lorenzin and Abanades, 2016). However, the low Prandtl number property of liquid metals ($Pr \sim 0.01$) leads to a scale separation between the thermal and viscous boundary layers, which poses a challenge to the modelling of turbulent heat fluxes. Besides, measurements for different kinds of heavy liquid metals is not simple. Many measurement corrections are needed to account for various conditions, especially in the local quantities measurement (Schulenberg and Stieglitz, 2010). Thus highly-resolved numerical prediction is the other powerful tool to study complex flows and provide reliable reference data.

Flow separation and reattachment due to sudden changes of the cross section are of crucial importance for the thermal-hydraulic characteristics of various engineering applications like heat exchangers, combustion chambers, thermal storage containers, electronic equipment and urban buildings. Because their frequency occurrence may result in drastic change of the mechanical and heat transfer performance, thus from the perspective of engineering practice, it is quite essential to understand the mechanism of flow and heat transfer in separating and reattaching flows (Kondoh et al., 1993). Turbulent flow over a backward-facing step is a good representative of this situation, as it features an adverse pressure gradient, flow separation and reattachment. Thus, this simple geometry is often chosen as the generic benchmark case for turbulence and heat transfer models (Blackwell and Armaly, 1993).

During the past several decades, many studies have been conducted in relation to this geometry and mostly only focused on the flow field. Experimentally, Armaly et al. (1983) used laser Doppler velocimetry (LDV) to investigate the velocity distribution and reattachment length (X_r) for laminar, transitional and turbulent flow of air in a backward-facing step. The X_r firstly increases with Reynolds number (Re) in laminar flow, then decreases in transitional region, lastly is independent of Re in turbulent flow. Jovic and Driver (1994) conducted an air flow at a moderate Re to provide data comparison for a direct simulation by

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Nomenclature

C_f	skin friction coefficient, $C_f = \frac{\tau_w}{0.5\rho u_b^2}$
ER	expansion ratio, $ER = H/(H-h)$
H	height
h	step height
$<k>$	turbulent kinetic energy, $<k> = \frac{1}{2}\langle u_i' u_i' \rangle$
L	length of the extent
Nu	Nusselt number,
Pr	molecular Prandtl number,
p	pressure
$\dot{q}$	heat flux density
Re_h	bulk Reynolds number, $Re_h = \frac{u_b h}{\nu}$
Re_τ	friction Reynolds number, $Re_\tau = \frac{u_\tau h}{\upsilon}$
St	Stanton number, $St = \frac{Nu}{Re \cdot Pr}$
T	Dimensionless temperature, $T = \frac{T^* - T_{in}^*}{\Delta T}$
ΔT	characteristic temperature increase, $\Delta T = \frac{\dot{q}}{\rho C_p U_b}$
T_{in}	inlet temperature
T_τ	friction temperature, $T_\tau = \frac{\dot{q}}{\rho C_p u_\tau}$
t'	fluctuating dimensionless temperature
u,v,w	velocity components
U_b	bulk velocity
U_c	convection velocity
u_τ	friction velocity, $u_\tau = \sqrt{\frac{\tau_w}{\rho}}$
x	streamwise coordinate
X_r	reattachment length
X^*	location of the maximum heat transfer
y	wall-normal coordinate
y^*	perpendicular distance to the heating wall
z	spanwise coordinate

Greek symbols

α	molecular heat diffusivity
α_t	turbulent heat diffusivity
$\hbar$	convective heat transfer
λ	thermal conductivity
ν	kinematic viscosity
ν_t	turbulent viscosity
ρ	density
C_p	specific heat capacity
μ	dynamic viscosity
τ_w	wall shear stress, $\tau_w = \left|\mu \frac{d\langle u^*\rangle}{dy^*}\right|_{y^*=0}$

Miscellaneous

$\langle\cdot\rangle$	averaging operator in time and spanwise direction
$(\cdot)^*$	dimensional quantity
$(\cdot)^T$	transpose operator
$(\cdot)'$	fluctuation of a quantity
$(\cdot)^+$	normalized by friction velocity u_τ
rms	root mean square

Le et al. (1997). The inlet is a boundary layer velocity profile. Subsequently, Kasagi and Matsunaga (1995) conducted a similar Re air flow measurement by using the three-dimensional (3D) particle-tracking velocimetry (PTV), whose inlet is a developed channel flow profile. These two experiments fixed the Re and provided detailed data for first- or second-order statistics, which are often chosen to verify the accuracy of different numerical methods. Nie and Armaly (2004) conducted LDV measurements to map the boundaries of the reversed flow regions in a 3D backward-facing step. The reversed flow region demonstrates different behaviors in laminar, transition, and turbulent flow.

Experiments about heat transfer for backward-facing step are very limited, to the authors' knowledge, the most well-known experiment was conducted by Vogel and Eaton (1985) in a wind tunnel. Effects of Re, inlet boundary-layer thickness on the Stanton number (St) profiles had been investigated. Fluctuating skin-friction (C_f') instead of the mean C_f was found a great importance in controlling the heat transfer near the reattachment region, and the Reynolds analogy did not hold for flows with separation and reattachment. The relationship between the C_f' and the St profiles had also been observed by large eddy simulations (LES) performed by Avancha and Pletcher (2002) and Keating et al. (2004).

Besides the experiments, numerical investigations are divided into two categories according to the inlet Reynolds number. One is laminar inlet. Effects of Re, expansion ratio (ER), aspect ratio (AR) on the distributions of C_f and Nusselt number (Nu) were largely studied. Due to the existence of side wall, the velocity and thermal fields after the step remain 3D if the AR is not large enough (Iwai et al., 2000). A jet-like flow is developed in the separating shear layer adjacent to the sidewall, and its impingement on the stepped wall is responsible for the peak that develops in the Nu and for the minimum that develops in the X_r near the side wall (Armaly et al., 2002; Nie and Armaly, 2002). Nie and Armaly (2003) also investigated the buoyancy effect on the flow behavior, profiles of C_f and Nu in 3D case. The other one is turbulent inlet. Direct numerical simulation (DNS) method is mostly adopted to provide resolved flow and temperature data to improve the modelling of turbulent stresses and heat fluxes. Le et al. (1997) conducted a DNS simulation at $Re = 5100$ based on the step height and inlet free-stream velocity which is the same as the experiment (Jovic and Driver, 1994). Temporal behavior of spanwise-averaged reattachment point shows an approximately periodic oscillation. Large negative skin-friction in the recirculation region is ascribed to the low Re effects. Meri and Wengle (2002) studied the effect of the 2nd- and 4th-order spatial discretization order on DNS and LES simulations. Barri et al. (2010) used a dynamic method to generate realistic turbulent inflow conditions, which is compared well with the fully-developed channel flow. Though ER and Re are not the same, velocity statistics comparisons with the experiment data (Kasagi and Matsunaga, 1995) are generally in an excellent agreement. Kopera et al. (2014) conducted a higher $Re = 9000$ with fully-developed channel flow inlet. Tertiary corner eddy was shown clearly. The visualization of spanwise-averaged pressure fluctuations and streamwise velocity showed that the interaction of vortices with the recirculation bubble was responsible for the flapping of the reattachment position, which has a characteristic frequency.

It is obvious that the previous DNS simulations are mostly interested in the flow, heat transfer studies especially for liquid metals over backward-facing step are limited. In the 1990 s, Kondoh et al. (1993) studied 2D laminar heat transfer under isothermal heating boundary condition by conducting a series of simulations in which ER, Re and Pr were systematically changed. Detailed relationship between these three principle parameters and the fundamental heat transfer characteristics had been elucidated. Benefiting from European Horizon 2020 project SESAME (Roelofs et al., 2015), turbulent heat transfer over a backward-facing step for liquid sodium has gained more and more attention. A backward-facing step experiment set-up for sodium flow is under construction (Jaeger et al., 2017). Numerically, Niemann and Frohlich (2016) investigated a turbulent flow of liquid sodium over a backward-facing step at forced and buoyancy-aided mixed convection using DNS. The effect of buoyancy force on the flow and thermal field is prominent. Then they enlarged the Re from 4805 to 10,000 and studied the budgets of turbulent kinetic energy, Reynolds shear stress, temperature variance and turbulent heat flux transport equations (Niemann and Frohlich, 2017). Schumm et al. (2016, 2017)) conducted Reynolds-averaged

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