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The influence of pipe length on thermal statistics computed from DNS of turbulent heat transfer

S. Saha [a,*], C. Chin [a], H.M. Blackburn [b], A.S.H. Ooi [a]

[a] Department of Mechanical Engineering, University of Melbourne, Victoria 3010, Australia
[b] Department of Mechanical and Aerospace Engineering, Monash University, Victoria 3800, Australia

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ABSTRACT

We present results from direct numerical simulation of turbulent heat transfer in pipe flow at a bulk flow Reynolds number of 5000 and Prandtl numbers ranging from 0.025 to 2.0 in order to examine the effect of streamwise pipe length ($\pi\delta \equiv \pi D/2 \leqslant L \leqslant 12\pi\delta$) on the convergence of thermal turbulence statistics. Various lower and higher order thermal statistics such as mean temperature, rms of fluctuating temperature, turbulent heat fluxes, two-point auto and cross-correlations, skewness and flatness were computed and it is found that the value of L required for convergence of the statistics depends on the Prandtl number: larger Prandtl numbers requires comparatively shorter pipe length for convergence of most of the thermal statistics.

1. Introduction

Within the last decade, simulation procedures based on computational fluid dynamics (CFD) have become an essential design and analysis tool in a wide and ever-increasing range of applications involving fluid flow and heat transfer. Direct numerical simulation (DNS) is a well-accepted numerical tool among the most popular branches of CFD for high-fidelity solution of turbulent flows. From the time-dependent velocity and scalar fields obtained from DNS, a huge range of information such as single- and multi-point statistics can be readily calculated. This information is particularly useful when research demands accurate analysis of quantities that are difficult to measure experimentally, such as velocity and pressure gradients. Additional details from DNS have complemented existing experimental data and contributed significantly to the understanding of turbulence physics, and to the improvement of lower-order models.

Since the first successful DNS of turbulent channel flow and heat transfer at $Re_\tau = u_\tau\delta/\nu \approx 180$ (where u_τ is the friction velocity, δ is the half channel height or pipe radius, ν is the kinematic viscosity) for $Pr = \nu/\alpha = 0.1$, 0.71 and 2.0 (where α is the thermal diffusivity) by Kim and Moin (1989), many researchers have used DNS data to gain significant insight into the physics wall-bounded turbulent flow and heat transfer. Most of these simulations were performed for turbulent heat transfer in channel flow over a wide range of Reynolds numbers as well as Prandtl numbers with various configurations of thermal boundary conditions. By comparison, only a relatively limited number of DNS studies for turbulent heat transfer in non-buoyant pipe flow may be found in the literature as can be seen from an examination of Table 1. Typically if Prandtl number variations were examined, Re_τ had been comparatively low and conversely Prandtl number was often fixed (typically at $Pr = 0.71$, the value for air) if Re_τ variations were examined.

In the majority of these DNS studies the flow is assumed to be fully developed and hence it is justified to assume streamwise periodicity. However, other studies found that turbulence statistics may be affected by the length of the computational domain because large-scale streamwise structures, sometimes referred to as the "large-scale motions" (LSMs) may extend further than the streamwise periodic length. If the computational domain is too short, then the LSM can be "contaminated" by the enforced streamwise periodicity of the boundary conditions. If too long, then there is a wastage of computational resources. Hence, it is important to find the optimum length of the computational domain and to understand the effects on the DNS data that may result if simulations were conducted in a domain of insufficient length.

It was experimentally observed that the interaction between the outer layer and the inner layer in wall-bounded turbulent flow increased with increasing Reynolds number (Naguib and Wark, 1992). Kim and Adrian (1999) in their studies explained that very large-scale motions (VLSMs) in flat-plate boundary layers were much longer than LSMs appeared in the outer layer of a turbulent pipe flow. Monty et al. (2007) reported that the length of these long meandering structures in pipe and channel flows was up to 25δ.

* Corresponding author. Tel.: +61 3 8344 6748; fax: +61 3 8344 4290.
E-mail address: sumons@student.unimelb.edu.au (S. Saha).

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Table 1
Overview of turbulent heat transfer in wall-bounded flows.

Previous DNS	Re_τ	Pr	Boundary conditions
Channel flows			
Kim and Moin (1989)	180	[0.1, 0.71, 2.0]	UHG[1], UTD[2], PF[9]
Lyons et al. (1991)	150	1.0	UTD[2], CF[10]
Kasagi et al. (1992)	150	0.71	MBC[3], PF[9]
Kasagi and Ohtsubo (1993)	150	0.025	MBC[3], PF[9]
Kawamura et al. (1997)	180	[0.025, 0.05, 0.1, 0.2, 0.4, 0.6, 0.71, 1.0, 1.5, 5.0]	MBC[3], PF[9]
Abe et al. (1998)	[180, 395]	[(0.025, 0.1, 0.2, 0.4, 0.71, 5.0), (0.025, 0.2, 0.71)]	MBC[3], PF[9]
Matsubara et al. (1998)	150	[0.1, 0.3, 0.71, 1.5]	SMTG[4], PF[9]
Kawamura et al. (1998a)	180	[0.025, 0.05, 0.1, 0.2, 0.4, 0.6, 5.0]	MBC[3], PF[9]
Kawamura et al. (1998b)	180	[0.025, 0.05, 0.1, 0.2, 0.4, 0.6, 0.71, 1.0, 1.5, 5.0]	MBC[3], PF[9]
Kawamoto and Kawamura (1998)	180	[0.025, 0.05, 0.4, 0.71]	SMTG[4], PF[9]
Kawamoto and Kawamura (1999a)	180	[0.025, 0.71]	UTD[2], MBC[3], PF[9]
Kawamoto and Kawamura (1999b)	[180, 395]	[(0.025, 0.05, 0.1, 0.2, 0.4, 0.6, 5.0), (0.025, 0.2, 0.71)]	MBC[3], PF[9]
Kawamura et al. (1999)	[180, 395]	[0.025, 0.2, 0.71]	MBC[3], PF[9]
Matsubara et al. (1999)	150	0.71	SMTG[4], PF[9]
Johansson and Wikström (1999)	265	0.71	UTD[2], PF[9]
Na et al. (1999)	150	[0.3, 1.0, 3.0, 10.0]	UTD[2], PF[9]
Na and Hanratty (2000)	150	[1.0, 3.0, 10.0]	UTD[2], PF[9]
Kawamura et al. (2000)	[180, 395]	[(0.025, 0.2, 0.71, 1.0), (0.025, 0.2, 0.71, 1.0)]	UTD[2], MBC[3], PF[9], CF[10]
Kawamura and Ogawa (2001)	180	0.71	UTD[2], SMTG[4], CWTDSMTG[5], PF[9]
Matsubara et al. (2001)	150	0.71	MBC[3], SMTG[4], PF[9]
Piller et al. (2002)	150	[0.025, 0.05, 0.1, 0.3, 1.0]	UTD[2], PF[9]
Kawamura and Abe (2002)	[180, 395, 640]	[0.025, 0.71]	MBC[3], PF[9]
Abe and Kawamura (2002)	[180, 395, 640]	[0.025, 0.71]	MBC[3], PF[9]
Seki et al. (2003a)	[180, 395]	0.71	UTD[2], MBC[3], PF[9]
Seki et al. (2003b)	180	0.71	UTD[2], MBC[3], CWTDSMTG[5], PF[9]
Abe et al. (2004)	[180, 395, 640, 1020]	[0.025, 0.71]	MBC[3], PF[9]
Tsukahara et al. (2004)	[64, 70, 80, 110, 150, 180]	0.71	MBC[3], PF[9]
Kawamura et al. (2004)	[180, 395, 640, 1020]	[0.025, 0.71]	MBC[3], PF[9]
Seki and Kawamura (2004a)	180	0.71	SVTBC[6], PF[9]
Seki and Kawamura (2004b)	180	0.71	UTD[2], MBC[3], CWTDSMTG[5], PF[9]
Seki and Kawamura (2005)	180	0.71	SVTBC[6], PF[9]
Seki and Kawamura (2006)	180	0.71	SVTBC[6], PF[9]
Seki et al. (2006)	180	[0.71, 1.0, 2.0, 10.0]	MBC[3], PF[9]
Abe et al. (2008)	[180, 395, 640]	0.71	MBC[3], PF[9]
Antonia et al. (2008)	[180, 395, 640, 1020]	0.71	MBC[3], PF[9]
Yamamoto et al. (2009)	[150, 1000, 2000]	5.0	UTD[2], PF[9]
Pipe flows			
Satake et al. (2000)	[150, 180, 360, 500, 1050]	0.71	MBC[3], PF[9]
Piller (2005)	180	0.71	IWT[7], IWHF[8], MBC[3], PF[9]
Redjem-Saad et al. (2007)	186	[0.026, 0.1, 0.2, 0.4, 0.71, 1.0]	MBC[3], PF[9]
Saha et al. (2010)	170	[0.026, 0.1, 0.2, 0.4, 0.71, 1.0]	MBC[3], PF[9]

[1] USG: uniform heat generation with cold isothermal walls.
[2] UTD: uniform temperature difference (constant wall temperature difference).
[3] MBC: mixed boundary condition (wall temperature is time independent and varies linearly along streamwise direction).
[4] SMTG: spanwise mean temperature gradient (time-averaged wall temperature is uniform in streamwise and wall-normal direction).
[5] CWTDSMTG: constant wall temperature difference imposed with spanwise mean temperature gradient.
[6] SVTBC: streamwise varying thermal boundary condition.
[7] IWT: ideal isothermal boundary condition (time-averaged wall temperature is uniform and constant).
[8] IWHF: ideal isoflux boundary condition (time-averaged wall temperature varies linearly along streamwise direction).
[9] PF: Poiseuille flow.
[10] CF: Couette flow.

For DNS of turbulent channel flow with passive scalar transport, Kawamura et al. (2004) inspected the very large-scale structures of temperature fluctuation for a range of Reynolds numbers and observed the existence of VLSMs in the outer region which was closely related to "temperature front" phenomenon reported by Chen and Blackwelder (1978). With decreasing Prandtl number, near-wall streak structures become more elongated, demanding longer computational domains.

Computational cost typically increases with increasing Reynolds and Prandtl numbers in order to resolve all relevant length scales in the simulation. However, in general, our results will show the length of the pipe will need to be increase with decreasing Prandtl numbers. This is because we have to consider the need to correctly capture all key dynamical features of the LSMs and VLSMs in wall-bounded flows, computational domain sizes must be chosen carefully. In wall-bounded turbulent flows, computational cost estimated by Jiménez (2003) to scale with $\sim L_x^2 L_y Re_\tau^4$. Moreover, the ratio between the largest and the smallest length scales in thermal field is roughly proportional to $Re^{3/4}Pr^{1/2}$ at higher Prandtl numbers (Tennekes and Lumley, 1972). As a result, the computational cost for a wall-bounded thermal turbulence simulation can be approximated as $\sim L_x^2 L_y Re_\tau^4 Pr^{3/2}$ (Kasagi and Iida, 1999). It is also important to consider that the most energetic small-scale structure for temperature fluctuations is found at a streamwise wavelength of $\lambda_x^+ \approx 700$ (Yamamoto et al., 2009) whereas that for velocity fluctuations has a streamwise length of $\lambda_x^+ \approx 1000$ (Marusic et al., 2010) suggesting the computational domain must use at least $l^+ \approx 1000$ in order to avoid any "contamination" by periodicity in the streamwise direction.

DNS studies for turbulent heat transfer in a channel have been carried out using a number of different boundary conditions for the flow and thermal fields: uniform heat generation with cold isothermal walls (Kim and Moin, 1989), uniform temperature difference (Kim and Moin, 1989; Yamamoto et al., 2009), mixed boundary condition (Kasagi et al., 1992; Saha et al., 2010),