LES OF MODERATE REYNOLDS NUMBER TURBULENT PIPE FLOWS

Cheng Chin[1] & Jason Monty [1] & Andrew Ooi [1]
[1]*Department of Mechanical Engineering, University of Melbourne, Victoria, Australia*

Abstract Wall-resolved large-eddy simulation of fully developed turbulent pipe flows are performed using a spectral vanishing viscosity approach. Turbulence statistics are compared with direct numerical simulation and hot-wire experimental data at similar friction Reynolds numbers $Re_\tau = 1002$. Turbulence statistics of streamwise velocity show good agreement up to the fourth order. The results highlight the feasibility of using wall-resolved large-eddy simulation to accurately investigate turbulent pipe flow at Reynolds numbers not currently feasible for direct numerical simulation. Further simulations have been performed at $Re_\tau \approx 2000$, preliminary results compared well to DNS data and will be presented in the conference and full paper.

INTRODUCTION

The need to investigate fundamental wall-bounded turbulence at high Reynolds number is widely agreed in open literature. In the present age, accurate high Reynolds number data are still primarily achievable only via well designed experimental methods. With the progress of computational technology, simulations have emerged to play a vital role in the research of wall-bounded turbulence. The effects of low Reynolds number is already well documented [1]. In addition, turbulence statistics that are scaled with inner variables are dependent on Reynolds number. Therefore there is a need for higher Reynolds number DNS. In recent times, there have been moderate Reynolds number DNS of turbulent pipe flows performed by [6, 2] up to Reynolds number of $Re_\tau \approx 2000$. This Reynolds number is considered modest compared to turbulent pipe flow experiments carried out by [7, 4], with a Reynolds number range of Re_τ $O(10^3 - 10^5)$. In comparison to DNS, however, LES has not been as well received as an accurate tool for fundamental wall-bounded turbulence research. There have been on-going efforts in the formulation of more accurate LES models, but comparatively few simulations have been performed at high Reynolds number. The aim of the present work is to carry out wall-resolved LES and to compare outcomes to those obtained by DNS and HWA at matched Reynolds number. The DNS data is from [2] and the experimental data is from [4]. By demonstrating the accuracy of turbulence statistics we hope to advocate for the future use of wall-resolved LES for the simulation of high Reynolds number wall-bounded turbulent flows. The LES simulation has grid points of approximately 40×10^6 as compared to the DNS with grid points of 590×10^6. This corresponds to computational saving of the order $O(10)$.

Our LES methodology employs the 'spectral vanishing viscosity' (SVV) approach. SVV has previously shown promising outcomes when applied to turbulent pipe flow at $Re_\tau = 314$ by [3]. The streamwise, radial and azimuthal directions are denoted as x, r and θ, here we define $y = R - r$, where R is the pipe radius. The respective velocities are defined as U, U_r and U_θ with the corresponding fluctuating components as u, u_r and u_θ. The computational streamwise domain length is $L_x = 8\pi R$. For the LES simulations, the spatial discretization is fully spectral with Fourier expansions in the axial direction and with nodal-based spectral elements covering the pipe cross-section. The time-integration scheme is a second-order velocity-correction projection scheme. According to the recommendations of [5], a grid resolution sufficient for LES would be $\Delta r\theta^+ \approx 15$–40 and $\Delta x^+ \approx 50$–150. (The superscript '$^+$' denotes scaling with U_τ and ν.) Here, the LES has an axial grid resolution of $\Delta x^+ = 32.8$ and maximum $\Delta r\theta^+ = 19.7$, which is within or finer than the recommended grid resolutions. To perform a wall-resolved LES, the radial grid resolution has to be fine enough to represent the structures, hence the chosen number of grid points utilized in the radial direction is $N_r \approx 160$, yielding a first grid point off the wall at $\Delta y^+ = 0.048$. There are at least 25 grid points within the buffer layer $y^+ \approx 30$. Simulations parameters of the LES and DNS is shown in table 1.

Simulation	L_x	Re_τ	Δx^+	Δy^+	$\Delta r\theta^+$	N_x	N_r	N_θ	$\frac{TU_b}{L_x}$
DNS (▽)	$8\pi R$	1002	7.87	[0.03,8.2]	6.56	3200	192	960	12
LES (□)	$8\pi R$	1002	32.8	[0.048,9.84]	19.6	768	160	320	12

Table 1. Experimental conditions and computational parameters for both physical and numerical experiments.

RESULTS

Figures 1(a) and 1(b) display the mean velocity and turbulence intensity profiles, in inner scaling, for the simulations and experiment. The DNS is represented by triangle symbols, LES by squares and HWA by circles. The mean velocity profiles collapse remarkably well throughout the flow with the simulations capturing data within the linear sublayer, which is absent from the hot-wire data due to wall proximity limitations in the experiment. The turbulence intensity profiles agree well for most of the flow and behave as expected, peaking at an inner-scaled wall normal distance of $y^+ \approx 15$.
Next we compare the one-dimensional pre-multiplied streamwise velocity spectra non-dimensionalised with friction ve-

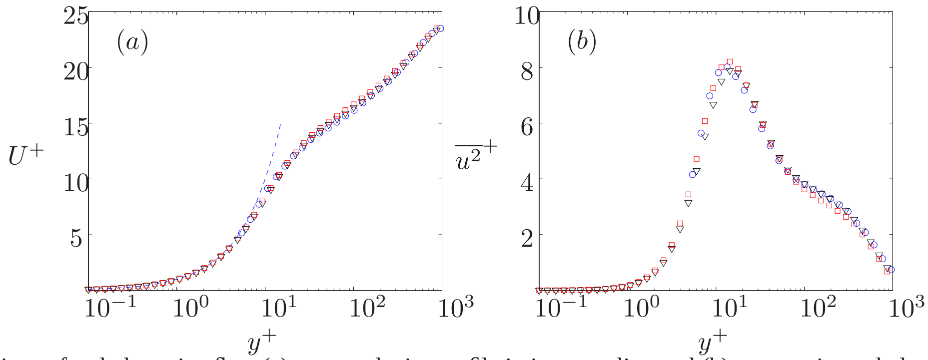

Figure 1. Comparison of turbulent pipe flow (a) mean velocity profile in inner scaling and (b) streamwise turbulence intensity profile in inner scaling from hot-wire measurement (blue ◯); DNS (black ▽) and LES (red □). Dashed line is $U^+ = y^+$.

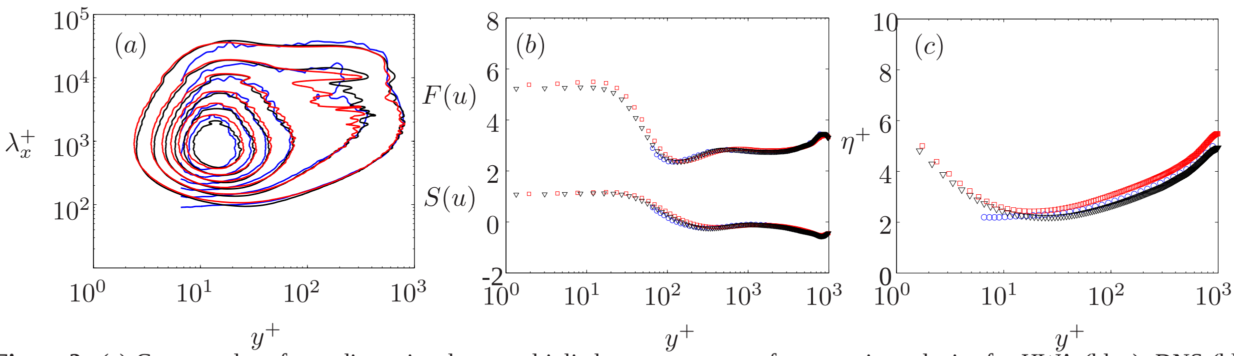

Figure 2. (a) Contour plot of one dimensional pre-multiplied energy spectra of streamwise velocity for HWA (blue), DNS (black) and LES (red). Contour levels of Φ_{uu}^+ start from 0.3 with increments of 0.3. (b) Profiles of skewness(lower) and kurtosis(upper). (c) Distribution of the dissipation scale in a fully developed turbulent pipe flow for $Re_\tau = 1000$. Symbols are as in figure 1.

locity $\Phi_{uu}^+ = k_x \phi_{uu}^+$, where k_x is the streamwise wavenumber. Figure2(a) displays this global view, and reveals several aspects that were not readily apparent when viewing single point comparisons. All spectrograms compare well except in the near-wall ($y^+ < 10$) for HWA, due to limitations of the experiment in obtaining near-wall information. Hence it reinforces the need for simulations, where near-wall data can be obtained with accuracy. Figure 2(b) displays the skewness and kurtosis profiles of the present DNS, LES and HWA. Skewness profiles are the lower profiles and kurtosis profiles are the upper profiles, with symbols retaining their meaning from figure 1. All profiles agree well throughout the entire turbulent flow with the DNS and LES being able to capture much more information very close to the wall. Once again the LES shows convergence with DNS even at high order statistics. Such excellent agreement of the higher order moments between DNS, LES and HWA, even in the far outer region, indicate that the simulations are very well converged.

It should be noted that a direct comparison of measurement resolutions is complicated for pipe flows by the fact that $\Delta(r\theta)^+$ decreases when moving away from the wall and is not a straightforward analogue to hot-wire length that Δz^+ is in a channel flow. Thus a more appropriate length scale to use when discussing measurement resolution may be the Kolmogorov length scale $\eta = (\nu^3/\langle\epsilon\rangle)^{1/4}$ where $\langle\epsilon\rangle$ is the mean dissipation rate. The distribution of the dissipation scale η^+ is displayed in figure 2(c) with symbols as in figure 1. All distributions display a similar profile. At the near-wall for $y^+ \lesssim 10$, the HWA data seems to remain constant when the DNS/LES data increase rapidly as the wall is approached.

It is evident from the results that wall-resolved LES at moderate Reynolds number can emulate DNS in generating accurate streamwise velocity turbulence statistics (up to fourth order). It is recommended that wall-resolved LES would be applicable even at very high Reynolds number.

References

[1] R. A. Antonia, M. Teitel, J. Kim, and L. W. B. Browne. Low-Reynolds-number effects in a full developed turbulent channel flow. *J. Fluid Mech.*, **236**:579–605, 1992.

[2] C. Chin, J. P. Monty, and A. Ooi. Reynolds number effects in DNS of pipe flow and comparison with channels and boundary layers. *Intnl J. Heat Fluid Flow*, **45**:33–40, 2014.

[3] K. Koal, J. Stiller, and H. M. Blackburn. Adapting the spectral vanishing viscosity method for large-eddy simulations in cylindrical configurations. *J. Comput. Phys.*, **231**:3389–3405, 2012.

[4] H. C. H. Ng, J. P. Monty, N. Hutchins, M. S. Chong, and I. Marusic. Comparison of turbulent channel and pipe flows with varying Reynolds number. *Expts Fluids*, **51**:1261–1281, 2011.

[5] U. Piomelli. Large-eddy simulations: where we stand. *Advances in DNS/LES*, pages 93–104, 1997.

[6] X. Wu and P. Moin. A direct numerical simulation study on the mean velocity characteristics in turbulent pipe flow. *J. Fluid Mech.*, **608**:81–112, 2008.

[7] M. V. Zagarola and A. J. Smits. Mean flow scaling in turbulent pipe flow. *J. Fluid Mech.*, **373**:33–79, 1998.