Mitteilung

Projektgruppe/Fachkreis: Turbulenz und Transition / Q2, Q2.1

Stochastic modeling of heat and momentum transfer in annular pipe flow: A one-dimensional turbulence study with comparison to DNS and LES

Marten Klein Pei-Yun Tsai Heiko Schmidt

Lehrstuhl Numerische Strömungs- und Gasdynamik, Brandenburgische Technische Universität (BTU) Cottbus-Senftenberg, Siemens-Halske-Ring 15A, D-03046 Cottbus
marten.klein@b-tu.de

The predictive capabilities of numerical simulations for applications with coupled heat and momentum transport crucially depend on the fidelity of the numerical approach and the applicability of models for the unresolved scales. This concerns wall-bounded flows in general and transfer-limited applications in particular since these require an accurate representation of the scalar and momentum boundary layers. In engineering applications, such as cylindrical heat exchangers (e.g. [1,2,3]) or chemical reactors (e.g. [4]), further complications arise due to spanwise wall curvature and modification of boundary layer profiles (e.g. [5,6]). A canonical flow configuration for such devices is heated annular pipe flow, which is sketched in Fig. 1(a). Fluid is confined between two concentric coaxial cylinders and an axial mean flow is driven by a prescribed axial pressure gradient. In addition, the fluid is weakly heated by a prescribed wall heat flux q_w or, alternatively, by isothermal inner and outer cylinder walls that are held at different temperature (not shown here).

In filter-based approaches like Reynolds-averaged Navier–Stokes simulation (RANS) or large-eddy simulation (LES), the ensemble effect of turbulence is usually modeled based on gradient-diffusion closure assumptions that date back to Boussinesq [7] for RANS and Smagorinsky [8] for LES, respectively. In these approaches, it is usually not feasible to resolve small-scale turbulence in the vicinity of the wall. Instead, wall models (WM) are used [9,10]. For RANS, this means bypassing details of near-wall turbulence by prescribed wall functions. For LES/RANS near-wall turbulence is resolved in an average sense, and it is partly resolved in WMLES while an additional set of equations for the unresolved wall-shear stress and surface heat flux is solved. Unfortunately, the predictive capabilities of these approaches can be very limited when the application case differs from the calibration case. This is demonstrated in Fig. 1(b) for radial profiles of the normalized mean axial velocity in concentric annular pipe flow that have been obtained with OpenFOAM [11] (version 9) using the wall-adapting local eddy-viscosity (WALE) model with default parameters that have been calibrated for channel flow. For various radius ratios, $\eta = R_\mathrm{i}/R_\mathrm{o}$, a strong dependence on the grid resolution (here labeled as low “l” and high “h”) can be discerned.

The mentioned shortcoming in wall modeling due to spanwise curvature effects is addressed in the present study with the aid of the stochastic one-dimensional turbulence (ODT) model [12] formulated for cylindrical geometry [13]. ODT is a dimensionally reduced flow model that has been utilized recently as stand-alone tool for forward-modeling temporal boundary layers [14], differentially diffusing scalars in turbulent channel flows [15,16,17], and variable-density effects in heated pipe flow [18]. The model has recently also been used as subfilter-scale [19] and wall [20] model in LES demonstrating fidelity improvements at affordable cost. In the present study, stand-alone ODT is utilized in order to address radial transport processes by modeling turbulent stirring motions by a stochastically sampled sequence of radial mapping events that punctuate the continuous molecular-diffusive flow evolution. Fig. 1(c) demonstrates in terms of radial profiles of the normalized mean temperature profiles that ODT predictions for weakly heated annular pipe flow at moderate friction Reynolds $(Re_\tau \sim 300)$ and Prandtl $(Pr = 0.7)$ numbers are in reasonable agreement with available reference DNS. A similar level of fidelity is obtained for the ODT mean axial velocity (not shown here). As in the case of the LES mentioned above, ODT model parameters have been kept fixed after calibration for channel flow [15,16] by making use of the model's predictive capabilities.

In the contribution, we will discuss how the heat and momentum transfer to the cylindrical domain walls depends on the geometric (radius ratio and thermal wall boundary condition) as well as physical (Reynolds and Prandtl number) control parameters. We will show that the stochastic model is able to capture radius ratio, Reynolds, and Prandtl number effects for fixed model parameters and, thus, exhibits good predictive capabilities with respect to the mean. In addition, we will analyze low-order flow statistics and fluctuation budget balance equations for the radially asymmetric boundary layers over the inner and outer cylinder, respectively. We will demonstrate that small curvature radii affect boundary layer profiles also at high Reynolds numbers suggesting that wall modeling over spanwise curvature must be done carefully and may demand advanced modeling strategies for robust predictions.

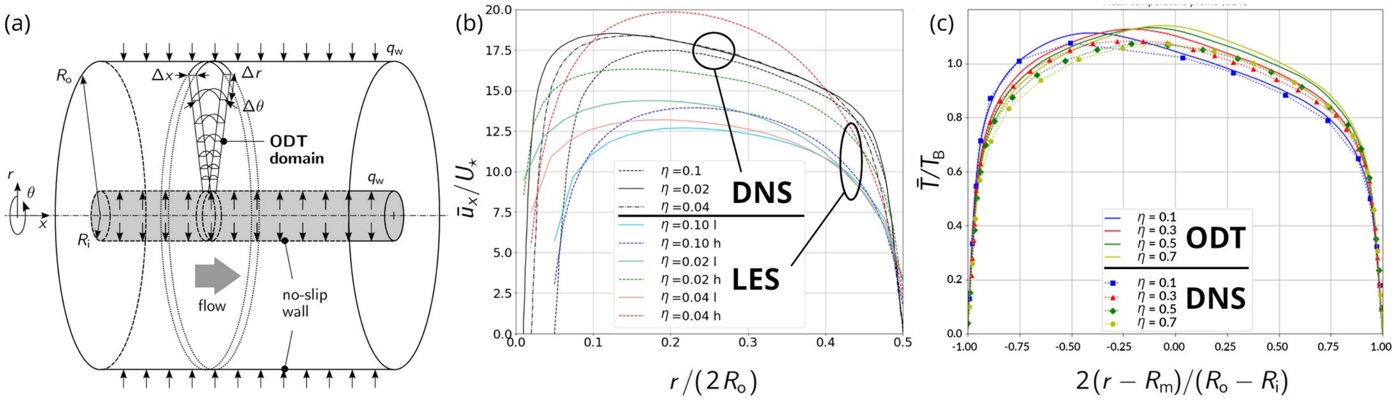

Fig. 1: (a) Sketch of the heated concentric coaxial pipe flow configuration investigated. (b) Radial profiles of the normalized mean axial velocity predicted by LES (OpenFOAM-9, WALE model) in comparison to reference DNS [6]. (c) Radial profiles of the normalized mean temperature predicted by ODT in comparison to reference DNS [3]. For both, ODT and WALE, model parameters originally calibrated for channel flow were used and kept fixed.

References

[1] S. Y. Chung, G. H. Rhee, H. J. Sung, *Int. J. Heat Fluid Flow* **23:**426–440, 2002.
[2] S. Y. Chung, H. J. Sung, *Int. J. Heat Fluid Flow* **24**(3):399–411, 2003.
[3] E. Bagheri, B.-C. Wang, *Phys. Fluids*, **33**(5):055131, 2021.
[4] E. Balestrin, S. M. Arruda Guelli Ulson de Souza, J. A. B. Valle, A. da Silva, *Chem. Eng. Res. Design*, **170**:90–106, 2021.
[5] J. M. Nouri, H. Umur, J. H. Whitelaw, *J. Fluid Mech.* **253**:617–641, 1993.
[6] B. J. Boersma, W.-P. Breugem, *Flow Turbulence Combust.* **86**:113–127, 2011.
[7] J. Boussinesq, *Théorie Analytique de la Chaleur*, Vol. II, Gauthier-Villars, 1903.
[8] J. S. Smagorinsky, *Mon. Weather Rev.* **91**:99–164, 1963.
[9] U. Piomelli, *Progress Aerospace Sci.* **44**:437–446, 2008.
[10] J. Larsson, S. Kawai, J. Bodart, I. Bermejo-Moreno, *Mech. Eng. Rev.* **3**:1500418, 2016.
[11] H. G. Weller, G. Tabor, H. Jasak, C. Fureby, *Comput. Phys.* **12**(6):620, 1998.
[12] A. R. Kerstein, *J. Fluid Mech.* **392**:277–334, 1999.
[13] D. O. Lignell, V. B. Lansinger, J. A. Medina Méndez, M. Klein, A. R. Kerstein, H. Schmidt, M. Fistler, M. Oevermann, *Theor. Comput. Fluid Dyn.* **32**:495–520, 2018.
[14] Rakhi, M. Klein, J. A. Medina Méndez, H. Schmidt, *J. Turbul.* **20**(8):506–543, 2019.
[15] M. Klein, H. Schmidt, STAB/DGLR Symposium 2020, *NNFM* **151**:47–57, 2021.
[16] M. Klein, H. Schmidt, D. O. Lignell, *Int. J. Heat Fluid Flow*, **93**:108889, 2022.
[17] M. Klein, C. Zenker, H. Schmidt, *Chem. Eng. Sci.* **204**:186–202, 2019.
[18] J. A. Medina Méndez, M. Klein, H. Schmidt, *Int. J. Heat Fluid Flow* **80**:108481, 2019.
[19] C. Glawe, J. A. Medina Méndez, H. Schmidt, *Z. Angew. Math. Mech.* **98**:1907–1923, 2018.
[20] L. S. Freire, M. Chamecki, *Comput. Fluids* **230**:105135, 2021.