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Preliminary Study on Wall-modeled Large Eddy Simulation of Turbulent Heat Transfer for Liquid Rocket Engines

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Abstract

Wall-modeled large eddy simulation (WMLES) is performed toward simulation of turbulent heat transfer in liquid rocket engine flowfields. To assess the prediction capabilities of WMLES, as a preliminarily work, turbulent channel flows with heat transfer are simulated. The present results show that mean velocity and temperature profiles agree well with DNS and the log law from moderate to high Reynolds numbers. Outer-layer turbulence and its fluctuations of velocity and temperature are well captured with modeling the inner layer. Quantitative differences in the fluctuations are observed indicating that the assessment for the spatial accuracy of the numerical method is needed.

1. Introduction

The accurate prediction of heat transfer between freestream and walls has a large importance for the design of liquid rocket engine components. The combustion chamber wall is exposed to extremely high temperature burnt gas, and the heat transfer from the burnt gas to the wall results in the generation of high heat flux which sometimes leads to serious damages on the chamber wall. The heat flux is distributed non-uniformly on the wall depending on local flow and flame structures; thus, accurate prediction of heat transfer based on the understanding of the flow and combustion field in the chamber is important. In regenerative cooling channels, heat pick-up due to heat transfer from the wall to the coolant flow is essential for preventing the chamber wall damages and obtaining the energy to drive turbo-pumps. For the geometry design of the cooling channels to improve heat pick-up performance, wall-bounded turbulent flowfields inside the channel including secondary flow and flow separation is needed to be properly simulated.

Large eddy simulation (LES) can be a promising tool for simulating unsteady and complex turbulent flow in the engine components; however, LES of wall-bounded flows in practical engineering setting requires a huge computational cost. This is mainly due to the severe requirements in grid resolution for resolving turbulences in boundary layers at high Reynolds numbers (*Re*). [1] The number of grid points to resolve inner layer motions is proportional to $Re^{1.8}$, and this large Reynolds number dependency makes LES of wall-bounded flow challenging. To solve this problem, LES with wall-modeling approach, that is wall-modeled LES (WMLES), has been studied. The concept of WMLES is to directly resolve large-scale eddies in the outer layer while eddies in the inner layer are modeled. A number of wall-modeling approaches have been proposed and applied for wall-bounded turbulent flows. [1], [2] Recently, Kawai and Larsson [3] have founded that matching location of the wall model and LES should be located further away from first grid points off the wall because the LES solution include numerical errors at near-wall grid points. They also have proposed equilibrium and non-equilibrium wall models, and these models demonstrated its accuracy for high Reynolds number flows such as a supersonic shock/boundary layer interaction [4] and a separated flow over an airfoil.[5]

Primary interest of previous works on WMLES is prediction of velocity field and the wall shear. For turbulent heat transfer problems, limited WMLES studies [6], [7] can be found, and capability of WMLES is not well examined for prediction of temperature fields and heat transfer. Additionally, toward the near-wall modeling of LES for the liquid rocket flowfields, complex near-wall physics should be considered such as drastic changes of thermodynamic properties relative to high pressure and low temperature conditions (i.e., supercritical or transcritical conditions), and wall effects on chemical reactions and flame. This is highly challenging and needed to be tackled in a step-by-step manner.

The present study applies WMLES with an equilibrium wall model for modeling near-wall turbulences. In the present study, as a preliminary work, we have performed WMLES on turbulent channel flows with heat transfer. The capability of WMLES is assessed for the prediction of mean velocity and temperature fields and these fluctuations in a wide range of Reynolds numbers.

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2. Numerical Method

The governing equations are three-dimensional compressible Navier-Stoke equations. Spatial derivative terms in the governing equations are evaluated by the SLAU[8] of AUSM family upwind-biased schemes to ensure computational stability toward the simulation in practical engineering flowfields. The MUSCL approach is adopted to obtain third-order accurate discretization. The third-order TVD Runge-Kutta [9] is used for the time integration. For the LES computation, Implicit LES approach[10] is employed, and thus no additional sub-grid scale model is explicitly added. The wall shear stress and heat flux are calculated by solving the inner layer wall-model. The wall model solves the equilibrium boundary layer equations [4];

$$\frac{d}{dy}\left[\left(\mu+\mu_{t,wm}\right)\frac{dU_{||}}{dy}\right]=0,$$

$$\frac{d}{dy}\left[\left(\mu+\mu_{t,\mathrm{wm}}\right)U_{||}\frac{dU_{||}}{dy}\right]+\frac{d}{dy}\left[c_p\left(\frac{\mu}{Pr}+\frac{\mu_{t,\mathrm{wm}}}{Pr_{t,\mathrm{wm}}}\right)\frac{dT}{dy}\right]=0,$$

where μ, c_p, $U_{||}$, and T are the viscosity, the isobaric specific heat, the wall-parallel velocity, and the temperature, respectively. The eddy viscosity $\mu_{t,\mathrm{wm}}$ is taken as

$$\mu_{t,\mathrm{wm}}=\kappa\rho\sqrt{\frac{\tau_w}{\rho}}y[1-\exp(-y^+/A^+)]^2,$$

where $y^+=\rho_w y u_\tau/\mu_w$ is the wall-distance in viscous units. u_τ, ρ and τ are the friction velocity, the density, and the shear stress. The subscript w denotes the value at the wall. The parameters are set to κ = 0.41, A^+ = 17, and $Pr_{t,\mathrm{wm}}$=0.9. The above equilibrium boundary layer equations are solved on a near-wall grid with boundary conditions. The near-wall grid is embedded in the LES grid and refined in the wall-normal direction with 39 grid points. Following the suggestion by Kawai and Larsson [3], the top boundary of the near-wall grid is located at fifth grid point off the wall of the LES grid. As boundary conditions of the wall model, the instataneous LES solutions ($U_{||}$ and T) at the matching point are used at the top boundary, and appropriate thermal boundary conditions are employed at the bottom boundary. After solving the wall-model equations, the wall shear stress and wall heat flux obtained in the wall model are fed back to the LES as wall boundary conditions.

3. Results

Figure 1 shows a schematic of the turbulent channel flow. This configuration is based on the DNS study performed by Abe et al.[11] Here, x, y, and z are the streamwise, wall-normal, and spanwise directions, respectively. The computational domain size $L_x\times L_y\times L_z$ is set to $16\delta\times2\delta\times6\delta$. Here, δ denotes channel half width. The grid is designed to resolve turbulences in the outer layer. Uniform grid spacing is used in the streamwise and spanwise directions of Δx=0.05δ and Δz=0.03δ. The first grid point normal to the wall is located at y=0.02δ, and smoothly stretched up to the center of the channel. The grid spacing based on viscous wall units in streamwise and spanwise directions are $\Delta x^+\approx51$, $\Delta z^+\approx31$, and at the first grid point normal to the wall is $y_1^+\approx20$ at Re_τ=1020. Here, $Re_\tau=u_\tau\delta/\nu$ is the Reynolds number based on the friction velocity and channel half-width. The number of grid points is 321×61×201. Periodic boundary conditions are employed in the streamwise and spanwise directions. As boundary conditions of the wall-model, no-slip and constant heat flux conditions are imposed. Random perturbations are added to the initial velocity field to trigger the development of turbulence. A source term that corresponds to the streamwise pressure gradient is added in

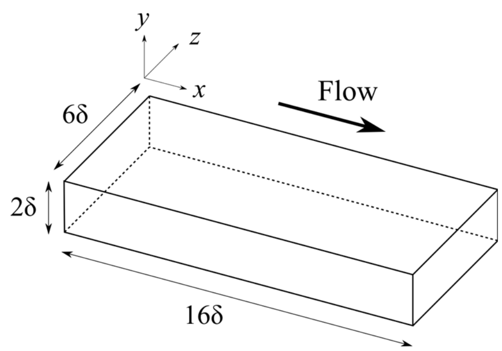

Figure 1: Schematic of channel flow.

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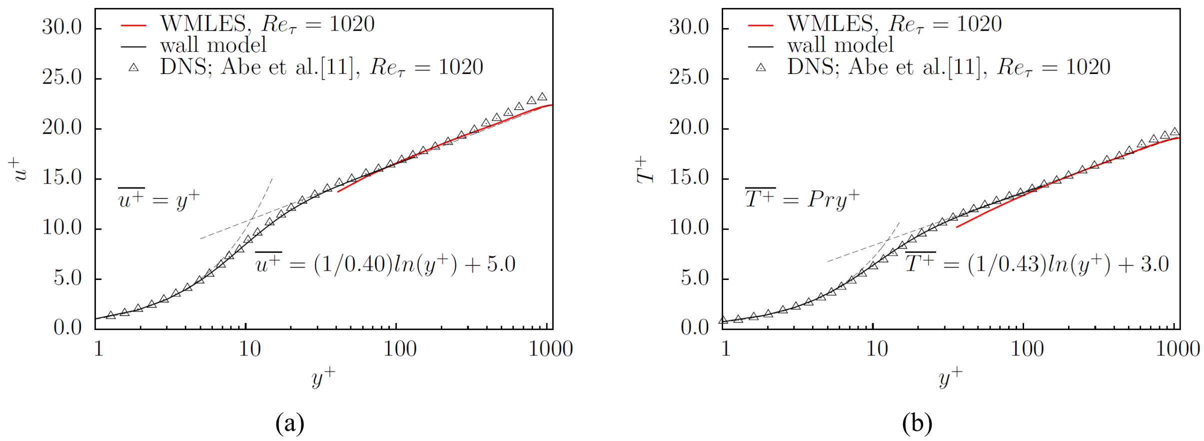

Figure 2: Mean profiles compared with DNS[11] and the log-law. (a) Mean streamwise velocity. (b) Mean temperature.

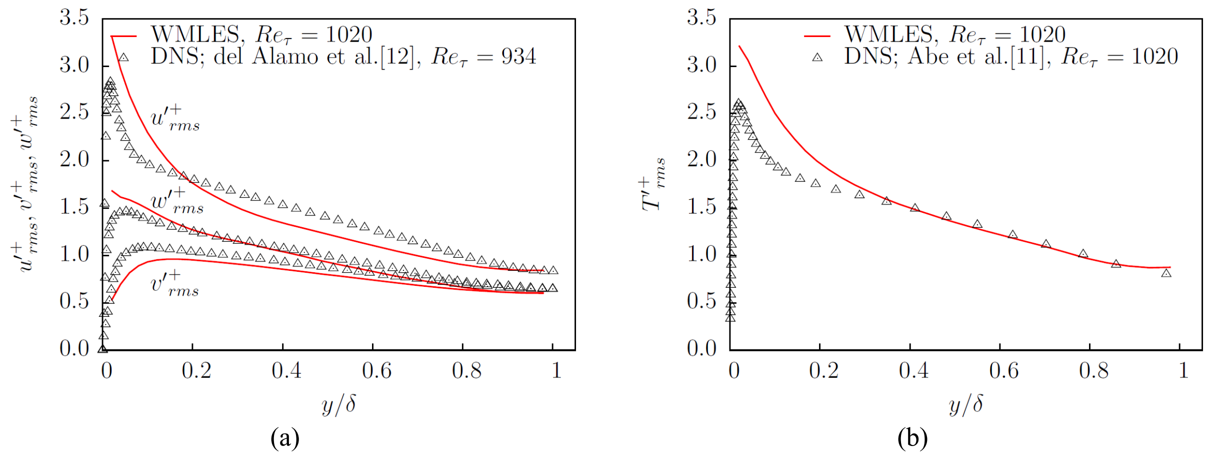

Figure 3: Root-mean-square (rms) velocity and temperature fluctuations at Re_τ=1020. (a) streamwise (top) , spanwise (middle), and wall-normal (bottom) velocity fluctuations compared with DNS at Re_τ=934[12]. (b) temperature fluctuation compared with DNS at Re_τ=1020[11].

the governing equations to maintain flow in the channel. The simulations are performed with a CFL number of approximately 0.6.

The Reynolds numbers Re_τ are set to 1020, 10,000, and 100,000. The Prandtl number is 0.72. The inlet pressure is 0.1 MPa. The Mach number is set to 0.1, such that the compressibility effect is negligible. The non-dimensional heat flux, which based on bulk velocity, temperature, and isobaric specific heat, of 1.3×10^{-4} is employed both top and bottom walls.

Figure 2 shows the mean velocity $u^+=u/u_\tau$ and temperature profiles $T^+=(T_w-T)/T_\tau$. Here $T_\tau=q_w/\rho c_p u_\tau$ is the friction temperature. The DNS results of channel flow with a constant wall heat flux condition obtained by Abe et al.[11]are also plotted. The results show good agreement with the DNS results and the log-lows in both velocity and temperature profiles. The solutions obtained by the wall model are also shown in Fig. 2. The velocity and temperature profiles in the modeled-inner layer are accurately predicted indicating that the inner layer is properly modeled in the wall model.

Figure 3 shows the velocity and temperature fluctuations as compared with the DNS results. The rms velocity and temperature fluctuations are normalized with the friction velocity and temperature. The DNS data of velocity fluctuations are obtained from the DNS of channel flow with the adiabatic wall at Re_τ=934,[12] and with the constant heat flux wall at Re_τ=1020.[11] The fluctuations of resolved turbulence away from the wall are obtained and in a reasonable agreement with the DNS data; nevertheless, the near-wall fluctuations in the unresolved-inner layer are not computed. Near wall region of $y/\delta\leq0.2$, quantitative overprediction of streamwise velocity and temperature fluctuations is found. These discrepancies seem to be caused by numerical dissipation. Similar discrepancies in the fluctuations are observed in the simulation of channel flow with a low-order scheme and a coarse grid.[13], [14] In WMLES, of course, the sufficient spatial accuracy and grid resolution must be applied for resolving the outer layer turbulence in the sense

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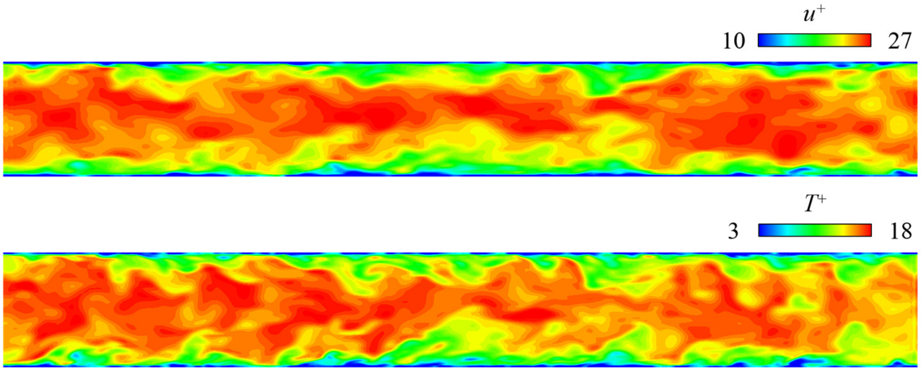

Figure 4: Instantaneous velocity temperature contours at *x-y* plane of Re_τ=1020.

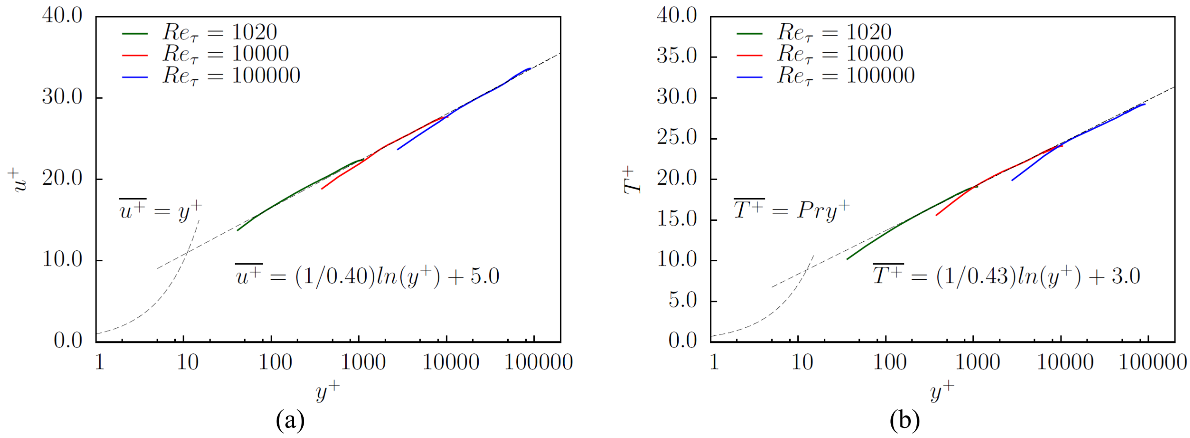

Figure 5: Mean profiles up to Re_τ = 100,000. (a) Mean streamwise velocity. (b) Mean temperature.

of LES. Further assessment of the spatial accuracy relative to the present numerics and the grid resolutions is needed. Instantaneous velocity and temperature contours for Re_τ=1020 are shown in Fig. 4. The results show large-scale structures having a length scale of the channel half width. The well-known analogy between the velocity and temperature fields, as shown in Ref. [15], is observed, and physically realistic turbulence is captured without resolving the wall modeled layer.

WMLES is performed with Re_τ up to 100,000, and the result is shown in Fig. 5. Note that the same computational grid is used in all cases. The log-law profiles are obtained even in high Reynolds numbers. This demonstrates the potential of WMLES in simulating turbulent heat transfer at very high Reynolds numbers with coarse near-grid resolution and a reasonable computational cost.

4. Conclusion

Toward the simulation of turbulent heat transfer in liquid rocket engines, the prediction accuracy of WMLES for the turbulent channel flow with heat transfer was investigated. Mean velocity and temperature profiles showed good agreement with the log laws and DNS data from moderate to high Reynolds numbers. In the instantaneous fields, physically realistic large-scale structures are well captured, and velocity and temperature fluctuations of the resolved turbulence were well predicted. Quantitative differences were observed particularly near the wall, and this was considered due to the accuracy of the numerical method and the grid resolution. As a next step, WMLES of practical flows such as heated channel with high Reynolds numbers will be performed.

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References

[1] U. Piomelli, Wall-layer models for large-eddy simulations, *Prog. Aerosp. Sci.*, vol. 44, no. 6, pp. 437–446, 2008.

[2] J. Larsson, S. Kawai, J. Bodart, and I. Bermejo-Moreno, Large eddy simulation with modeled wall-stress: recent progress and future directions, *Mech. Eng. Rev.*, vol. 3, no. 1, pp. 1–23, 2016.

[3] S. Kawai and J. Larsson, Wall-modeling in large eddy simulation: Length scales, grid resolution, and accuracy, *Phys. Fluids*, vol. 24, no. 1, 2012.

[4] S. Kawai and J. Larsson, Dynamic non-equilibrium wall-modeling for large eddy simulation at high Reynolds numbers, *Phys. Fluids*, vol. 25, no. 1, 2013.

[5] S. Kawai and K. Asada, Wall-modeled large-eddy simulation of high Reynolds number flow around an airfoil near stall condition, *Comput. Fluids*, vol. 85, pp. 105–113, 2013.

[6] N. Maheu, V. Moureau, P. Domingo, F. Duchaine, and G. Balarac, Large-eddy simulations of flow and heat transfer around a low-Mach number turbine blade, *Center for Turbulence Reserach, Proceedings of Summer Program 2012*, 2012.

[7] X. I. A. Yang, J. Urzay, and P. Moin, Heat-transfer rates in equilibrium-wall-modeled LES of supersonic turbulent flows, *Center for Turbulence Research Annual Research Briefs 2016*, 2016.

[8] E. Shima and K. Kitamura, Parameter-Free Simple Low-Dissipation AUSM-Family Scheme for All Speeds, *AIAA Journal*, vol. 49, no. 8, pp. 1693–1709, 2011.

[9] S. Gottlieb and C.-W. Shu, Total Variation Diminishing Runge-Kutta Schemes, *Math. Comput.*, vol. 67, no. 221, pp. 73–85, 1998.

[10] J. P. Boris, F. F. Grinstein, E. S. Oran, and R. L. Kolbe, New insights into large eddy simulation, *Fluid Dyn. Res.*, vol. 10, no. 4–6, pp. 199–228, 1992.

[11] H. Abe, H. Kawamura, and Y. Matsuo, Surface heat-flux fluctuations in a turbulent channel flow up to Ret = 1020 with Pr = 0.025 and 0.71, *Int. J. Heat Fluid Flow*, vol. 25, no. 3, pp. 404–419, 2004.

[12] J. C. del Alamo, J. Jimenez, P. Zandonade, and R. D. Moser, Scaling of the energy spectra of turbulent channels, *J. Fluid Mech.*, vol. 500, pp. 135–144, 2004.

[13] W. Cabot, Local dynamic models in channel flow, *Center for Turbulence Research Annual Research Briefs 1994*, pp. 143–159, 1994.

[14] S. Matsuyama, Performance of all-speed AUSM-family schemes for DNS of low Mach number turbulent channel flow, *Comput. Fluids*, vol. 91, pp. 130–143, 2014.

[15] R. A. Antonia, H. Abe, and H. Kawamura, Analogy between velocity and scalar fields in a turbulent channel flow, *J. Fluid Mech.*, vol. 628, pp. 241–268, 2009.