Comparison of LBM-RANS and LBM-VLES for 3D Taylor-Green Vortex Problems

A. Jammalamadaka, Y. Li, R. Zhang and H. Chen
Corresponding author: yanbing.li@3ds.com
Dassault Systemes, 175 Wyman St, Waltham, MA 02451.

Abstract: The Taylor-Green vortex (TGV) serves as one of the canonical flow problems developed to study the generation of small scales by three-dimensional vortex dynamics and the transition of flow field from well-organized large scale motion into decaying turbulence. A Lattice-Boltzmann Method (LBM) based numerical method is applied in this study to solve the time accurate three dimensional flow field at high Reynolds number. LBM describes a fluid flow in terms of a discrete kinetic equation on the particle density distribution function (the Lattice Boltzmann equation). The key advantages in LBM include extreme simple formulation with very low numerical dissipation, efficient parallel performance for time dependent flows and ease of modeling various complex fluids, which make it well suited for the computation of this flow. The flow turbulence is realized through an effective particle-relaxation-time scale in the kinetic equation. In the current study, two turbulence modeling approaches are investigated: LBM-RANS and LBM-VLES. In the LBM-RANS (Reynolds-Averaged Navier Stokes) approach, large scale coherent flow structures are resolved, while the effects of small scales turbulence are modeled via a Boussinesq eddy-viscosity approximation with two transport equations from extended renormalization-group theory. In the LBM-VLES (Very Large Eddy Simulation) approach, explicit small scale eddies are excited by strong dynamic interactions between the large scale resolved motions and small scale unresolved turbulence, which creates a broad range energy cascading between the two distinct turbulence spectrums. Simulations are performed using LBM-RANS and LBM-VLES for a TGV problem at Reynolds number 1600, detailed analysis including temporal evolutions of flow structures, power spectrums and decay rates of kinetic energy and dissipation rate, is made on the solutions from the two models and compared with solutions from direct numerical simulation (DNS). The comparisons indicated that LBM-RANS approach is over dissipative and cannot capture the vorticity dynamics correctly, while the LBM-VLES solution has been found to be consistent with results from DNS. In addition, TGV simulations at much higher Reynolds numbers ($Re=10^4 \sim 10^6$) are also performed beyond the reach of DNS. It is shown LBM-VLES is still able to capture to right turbulent structures and scaling laws for the inertial range, while it is over damped with LBM-RANS. This confirms the validity of the LBM-VLES approach for highly unsteady complex turbulent flow predictions. It should be noted that the same LBM-VLES model is been extensively used for a wide range of flow problems from aerodynamics, aeroacoustics, to heat transfer in automotive and aerospace industries.

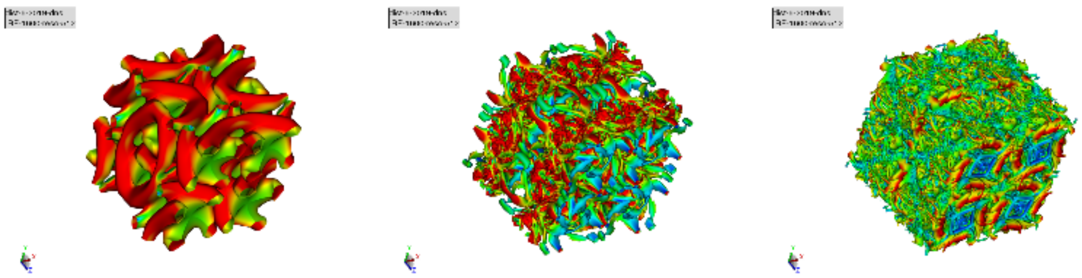

Figure 1: The temporal evolution of the TGV flow field. Left: Inviscid, Middle: coherent breakdown, Right: fully turbulent

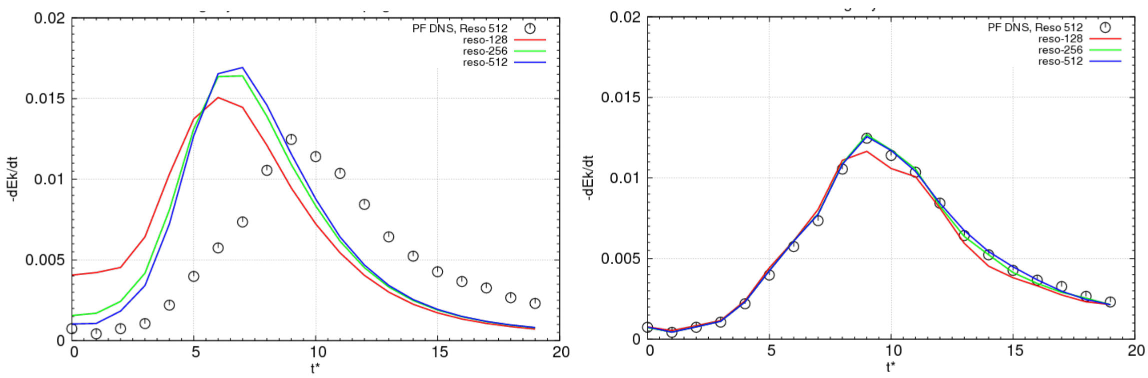

Figure 2: Evolution of Kinetic energy dissipation (Re=1600). Left: LBM-RANS, Right: LBM-VLES

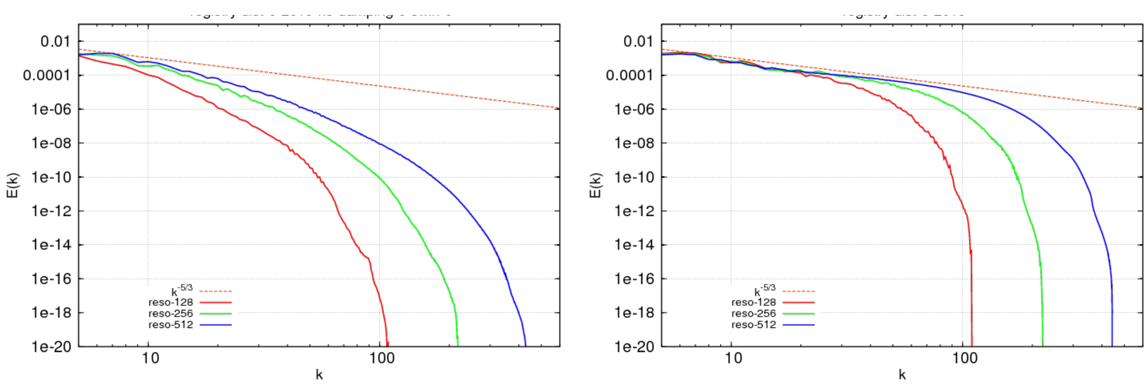

Figure 3: Comparisons of energy spectra for TGV flow at Re=10^6 (T*=9). Left: LBM-RANS, Right: LBM-VLES

Selected References

[1] Taylor, G. I. and Green, A. E. (1937), Mechanism of the Production of Small Eddies from Large Ones, Proc. R. Soc. Lond. A, 158, 499–521

[2] Chen, H., Chen, S. and Matthaeus, W. (1992), "Recovery of the Navier-Stokes Equations Using a Lattice-gas Boltzmann Method," Phys. Rev. A, Vol. 45, pp. 5339-5342.

[3] Shan, X., Yuan, X., & Chen, H. (2006). Kinetic theory representation of hydrodynamics: A way beyond the Navier–Stokes equation. Journal of Fluid Mechanics, 550, 413-441

[4] Succi, S. (2001) The Lattice Boltzmann Equation: For Fluid Dynamics and Beyond. Oxford University Press, Oxford.

[5] Yakhot, V. and Orszag, S. A. (1986), "Renormalization Group Analysis of Turbulence. I. Basic Theory," J. Sci. Comput., Vol 1, No. 2, pp. 3-51

[6] Chen, H., Kandasamy, S., Orszag, S., Shock, R., Succi, S., and Yakhot, V. (2003), "Extended Boltzmann Kinetic Equation for Turbulent Flows," Science, Vol. 301, pp. 633-636