NUMERICAL SIMULATION OF WALL-BOUNDED TURBULENT FLOWS WITH LINEAR EFFECTIVE VISCOSITY MODEL: DRAG REDUCTION AND NEW MECHANISTIC INSIGHT

Chang-Feng Li* [a)], **Fu-Jun Guo***, **Yong-Chen Pan***, **Rui Wang***, **Bamin Khomami****

**School of Energy and Power Engineering, Jiangsu University, Zhengjiang, Jiangsu 212013, China*

***Department of Chemical and Biomolecular Engineering, University of Tennessee, Knoxville, TN 37996, USA*

Summary The efficacy of linear effective viscosity models in predicting the multi-stage transition between the onset of drag reduction (DR) and the maximum drag reduction (MDR) asymptote in wall-bounded turbulent flows has been examined. Our Reynolds stress model based computations demonstrates the ability of this class of models to not only predict DR but also capture important characteristics of turbulent drag reduced flows. MDR asymptote is achieved at relatively high simulated Re numbers, and the main DR affecting region is determined.

INTRODUCTION

The addition of few tens of parts per million of long-chain polymers to o wall bounded turbulent flows can lead to dramatic friction drag reduction [1,2]. In spite of a large amount of experimental and simulation studies, the fundamental drag reduction mechanism has remained under debate. Considering the extra stress tensor is due to the polymer adding in Newtonian flow of the modified Navier-Stokes equation, and simplifying the effective form similar to that of Newtonian flow. The viscosity profile growing linearly with the distance from the wall in the drag reduction flows is derived from the viscoelastic equation [3], as shown in Fig. 1. In a recent theory of drag reduction in wall turbulence, L'vov et al. [4] proposed that the polymer stretching gives rise to a self-consistent effective viscosity that increases with the distance from the wall. Such a profile reduces the Reynolds stress (i.e., the momentum flux to the wall) more than it increases the viscous drag; thus drag reduces.

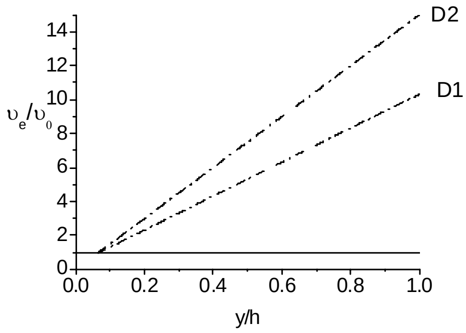

Fig. 1 The linear effective viscosity profiles

METHOD AND RESULTS

High Reynolds number flows can be simulated by Reynolds Stress Model (RSM), so with addition of the linear effective viscosity profile model, different drag reduction levels have been obtained under high flow conditions (see Fig. 2, the saturation phenomenon of drag reduction increasing is also observed). It is shown that turbulence drag reduction effect can be obtained from the model, and turbulence statistics, such as mean velocity and stress profiles, are consistent

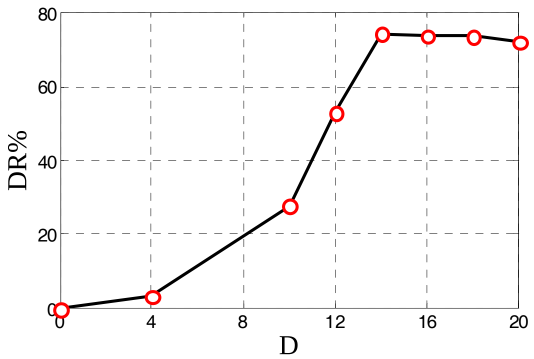

Fig. 2 The relationship between DR% and parameter D （$Re_m=2\times10^4$）

a) Corresponding author. Email: cfli@ujs.edu.cn with the experimental data and direct numerical simulation results [5,6]. In some aspects it is reasonable for this linear viscosity model to explain the turbulence drag reduction mechanism.

In order to find out the main affecting region of drag reduction, three regions has been built analogy to the original effective viscosity model: viscous sublayer, effective viscous layer and core region. Decreasing the polymer effective viscous region gradually as schematically illustrated in Fig. 3a, and investigating the drag reduction change. Simulation results shows that in LDR (low drag reduction) regime the main drag reduction affecting region is small (within the region of nondimensional wall distance y^+<100), while in HDR-MDR (high drag reduction – maximum drag reduction) regime the main affecting region is large (y^+ close to about 200 as MDR approaching).

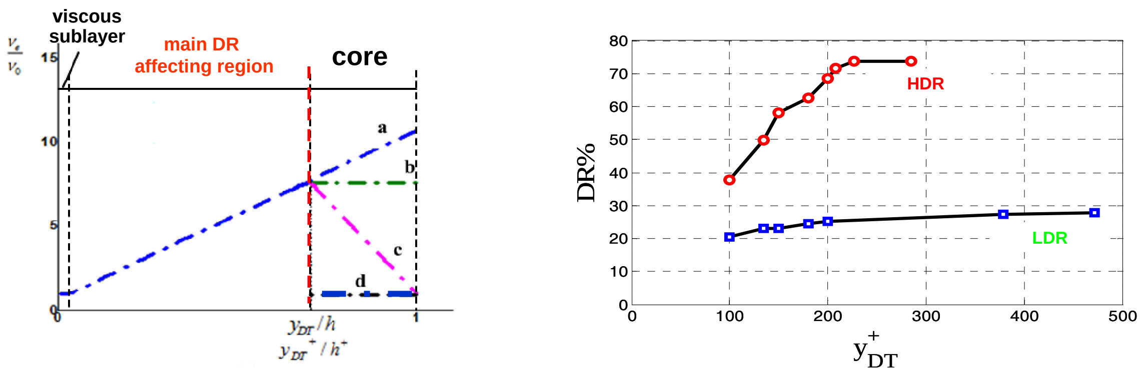

Fig. 3 The main drag reduction affecting region determination in wall-bounded turbulent flow
(a) Manipulation of the effective viscosity profile in the channel; (b) The relationship between DR% and manipulated position y_{DT}

SUMMARY AND DISCUSSION

The linear effective viscosity drag reduction models in wall bounded turbulent flows have been verified in combination with Reynolds stress turbulence model (RSM), and our computations demonstrate the ability of this class of models to not only predict drag reduction but also capture important characteristics of turbulent drag reduced flows.
The maximum drag reduction asymptote has been obtained in somewhat high bulk Reynolds number flows. The multi-stage transition between the onset of drag reduction and the maximum drag reduction, and the saturation of the slope of the effective viscosity model has been observed, implying the maximum drag reduction regime is the edge of turbulent state which is in agreement with the theory proposed in [6,7].
The main drag reduction affecting region has been determined. In the low drag reduction (LDR) regime this region is confined to 100 wall units from the wall, while in high drag reduction and maximum drag reduction regimes this region is enlarged to 200 or more wall units. These can give some reasonable explanation for the Virk's elastic sublayer and energy containing eddy size enlargement in wall-bounded drag reduction flows.

References

[1] Toms BA. Some Observation on the Flow of linear polymer solutions through straight tubes at large Reynolds number. *In Proc. 1st Inter. Cong. on Rheology*, 1948. 2: 135-141.
[2] Virk P S, Merri ll E W, Mickley H S, Smith K A, Mollo-Christensen E L. The Toms phenomenon: turbulent pipe flow of dilute polymer solutions. *Journal of Fluid Mechanics*, 1967, 30: 305- 328.
[3] Wang R., Li C.-F., Wu G.-F., Hu Z.-C., Wang Y.-H., Validation of effective viscosity model for polymer drag reduction in wall bounded turbulent flow. *Chinese Quarterly of Mechanics*, 2011, 32(2): 250-255.
[4] L'vov VS, Pomyalov A, Procaccia I, Tiberkevich V. Drag Reduction by Polymers in Wall bounded Turbulence. *Phys Rev Lett*, 2004, 92: 244503.
[5] Li CF, Sureshkumar R, Khomami B. Influence of rheological parameters on polymer induced turbulent drag reduction. *J. Non-Newton. Fluid Mech*, 2006, 140: 23-40.
[6] Angelis E D, Casciola CM, L'vov VS, Pomyalov A, Procaccia I, Tiberkevich V. Drag Reduction by a linear viscosity profile. *Phys Rev E*, 2004, 70: 055301.
[7] Benzi R., De Angelis E., L'vov VS, Procaccia I., Identification and calculation of the universal asymptote for drag reduction by polymers in wall bounded turbulence. *Phys Rev Lett*, 2005, 95: 194502.