EXPERIMENTAL AND NUMERICAL INVESTIGATION OF TURBULENT ENTRAINMENT IN DILUTE POLYMER SOLUTIONS

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Abstract Dilute polymer effects on the inter-scale energy transfer in turbulent flows is studied in this work with a major focus on the problem of turbulent entrainment across turbulent/non-turbulent interface. Polymers alter this region of flow significantly due to the large gradients at the interface and strong interaction of multiple scales - large scales that deflect the interface and the small scales that diffuse the vorticity and strain. An experimental (PIV) and numerical (DNS with FENE-P model) study has been performed to characterize the basic mechanisms of turbulent entrainment in Newtonian vs poly(ethylene oxide) solutions. We work on a localized patch of turbulent flow created numerically or by a small spherical oscillating grid, isolating the effects of boundary friction effects from the bulk effects. We analyze the patch initial growth, a steady state and the decay phase. The effects are quantified in terms of the reduced growth rates, turbulent kinetic energy and enstrophy balance, curvature of the interface and summarized by the reduced entrainment rates. Numerical model allows to reveal the underlying mechanism that controls the rates of turbulent energy transfer towards and across the interface and to further improve models of turbulent entrainment.

INTRODUCTION AND METHODS

Many practical flows are characterized by the coexistence of turbulent and non-turbulent regions such as jets, wakes or mixing layers. The dynamics of the turbulent/non-turbulent interface and the related turbulent entrainment directly influences important flow properties like mixing rates or heat and momentum transport. In order to further improve understanding of the interface dynamics in presence of dilute polymers in the fluid, a combined experimental and numerical approach is taken. We are focusing on a turbulent/non-turbulent interface that is not effected by boundary friction effects. The life cycle of the generated flow patch is studied within three phases: initial growth, a steady state and the decay phase after the forcing has been abruptly ceased.

In the experimental study a vertically oscillating spherical grid, schematically shown in figure 1, is used in order to avoid any regions of the flow where the generated turbulent flow field is directly in contact with a quiescent solid wall. The Particle Image Velocimetry (PIV) technique is applied to measure velocity fields of water for the Newtonian case and poly(ethylene oxide) with a molecular weight of 18×10^6 that is active at very low concentrations (of 5 and 10 wppm). Bottom panel of Figure 1 shows a snapshot of half of the generated patch, colored by the absolute vorticity levels. It is evident that the scales of the turbulent flow, the growth mode and size of the patch are all strongly influenced by the presence of the polymers, with the effect being stronger for higher concentration.

The numerical investigation is performed using a pseudo-spectral simulation of the Navier Stokes equations with the FENE-P model for the polymer stress [1]. The domain is tri-periodic with up to 384^3 discretization points. The forcing effect of the grid is mimicked by a body-force in a cross sectional slice of the domain. The propagation of the generated

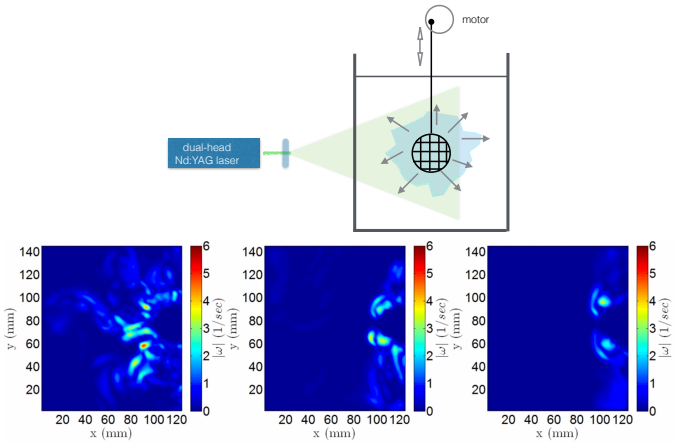

Figure 1: (Above) Sketch of the experimental setup, (below) vorticity-colored flow maps of one half of the patch at a certain time instant, in water, 5 and 10 wppm, from left to right.

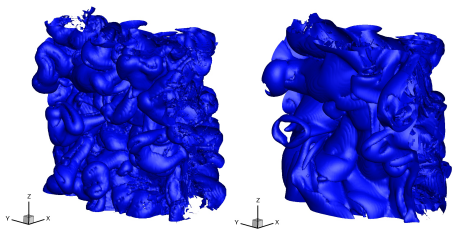

Figure 2: Vorticity iso-surfaces from the DNS simulation for the Newtonian case (left) and the case with polymers (right)

flow motion is monitored in the direction normal to this slice. Figure 2 shows isosurfaces of enstrophy for the Newtonian and the polymer case. The presence of the polymers strongly influences the generated flow leading to a smoother and less convoluted turbulent/non-turbulent interface.

RESULTS

As an exemplary result we show the evolution of the average turbulent kinetic energy in the patch during the entire cycle for both, experimental and the numerical study in figure 3. In both studies we have applied a statistically steady forcing for a given amount of time. Afterwards the forcing is switched off. It can be seen that the level of kinetic energy in the generated flow reaches a steady state after an initial ramp up phase and then decays once the forcing is switched off. Overall, the turbulent kinetic energy of the generated flow field is lower with the polymer (and decreases with increasing polymer concentration). Higher frequency of the grid causes a higher average kinetic energy for each solution and the evolution can be shown to follow a similar curve when nondimensionalized with the square of frequency.
While the experiment shows reduced growth rates under the presence of the polymer the numerical results reveal identical initial growth rates. The polymers only start to store part of the added energy after the flow is established. In order to clarify this apparent difference between experiments and numerics the energy input into the system will be analyzed in more detail. For this purpose, the experiment allows to measure the power input into the system directly so that it can be estimated whether the difference between Newtonian and non-Newtonian runs already originates from a different forcing power transmitted to the fluid. Further comparison between experiments and numerics include the growth rate of the turbulent patch, the balance of turbulent kinetic energy and enstrophy, curvature of the interface and summarized by the reduced entrainment rates. Moreover the DNS permits to directly measure the stresses induced by the polymers and study its effect on the propagation rates. The results obtained on previous works on enstrophy transfer mechanisms [2, 3] are extended here to the case of viscoelastic flows.

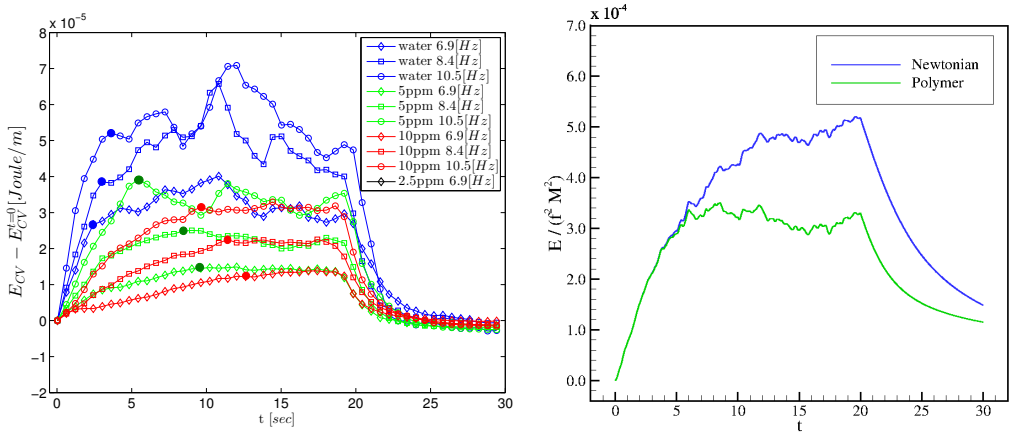

Figure 3: (left) Average turbulent kinetic energy in various runs of water (blue symbols), 5 wppm (green) and 10 wpppm (red), each for 3 frequencies: circles: 6.9 Hz, squares 8.4 Hz and triangles 10.5 Hz. (right) Numerical simulation results of the average TKE energy normalized by the forcing frequency f and by by the forcing mesh size M.

ACKNOWLEDGMENTS

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References

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