Enstrophy dynamics near a turbulent/non-turbulent interface for a viscoelastic fluid

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Abstract: Many flows are characterised by the coexistence of turbulent (T) and irrotational (or non-turbulent - NT) flow regions. Examples include wakes, jets, mixing layers and boundary layers. The two flow regions are separated by a very sharp turbulent/non-turbulent interface (TNTI) layer, which determines many important flow characteristics that involve the transfer of mass, momentum and energy *e.g.* heat[1]. When very long chains of molecules (polymers) are dissolved into an otherwise solvent Newtonian fluid the resulting medium exhibits complex viscoelastic properties that substantially affect the turbulence dynamics *e.g.* the energy cascade mechanism, through through complex interactions between the smallest velocity gradients and the polymer chains[2]. In some cases it has been shown that viscoelastic fluids present substantial less entrainment than Newtonian fluids, subjected to the same large scale constraints[2]. However, several of the detailed mechanisms governing the enstrophy near the TNTI layer need clarification, particularly at very high Reynolds numbers, where virtually no experimental data or numerical simulations have been reported so far. In the present work new massive DNS of viscoelastic fluids are carried out to analyse the enstrophy dynamics within the TNTI layer.

The new DNS and the subsequent analysis are based in several numerical tools previously reported (see [3] and references therein). The momentum equations are numerically integrated using a pseudo-spectral methods and the finitely extensible elastic model with the Peterlin closure (FENE-p) is used to compute the polymer stresses. We consider a shear free turbulence simulation[3] in a periodic box of dimensions $2\pi \times 2\pi \times 2\pi$ with $N = 768^3$ collocations points. To the author's knowledge these are the biggest DNS carried out so far for the FENE-p fluid. A total of 1 Newtonian and 4 viscoelastic simulations have been carried out, where the maximum relaxation time of the polymer molecules is equal to $\tau_p = [0.025, 0.05, 0.100, 0.200]\,s$.

Figure 1 shows iso-surfaces of vorticity magnitude corresponding to the irrotational boundary (IB) that constitutes the outer border of the TNTI layer separating T from NT fluid, for a Newtonian and two viscoelastic fluids. It is clear that the typical roughness associated with this interface is substantially altered for viscoelastic fluids, compared to the Newtonian case, where the IB is much more convoluted, which suggests that a substantial increase of the integral scale exists in these cases.

Figure 2 shows conditional mean profiles of enstrophy, kinetic energy and Taylor based Reynolds number, in relation to the irrotational boundary (IB) position (located at $y_I = 0$), where the irrotational and turbulent regions correspond to $y_I < 0$ and $y_I > 0$, respectively. The conditional enstrophy exhibits a sharp jump near the IB, which is also observed in the Newtonian case. The viscoelasticity substantially increases the turbulent fluctuations and consequently the Reynolds number, not also within the turbulent core region as in the NT region close to the TNTI layer.

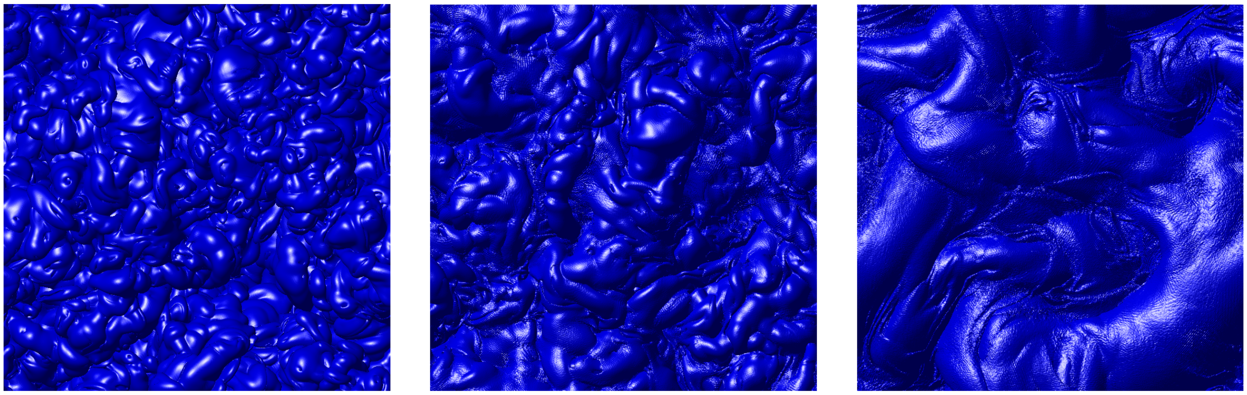
Finally, figure 3 shows the conditional enstrophy budgets for one Newtonian and two viscoelastic fluids. While for a Newtonian fluid the enstrophy production is roughly balanced by the enstrophy dissipation, in the viscoelastic case a new term arises - viscoelastic production - that can increase or decrease the enstrophy (depending on the value of τ) within the T region. This in turn affects the mechanism of generation of enstrophy in the TNTI layer, which modifies the entrainment rate characteristics of the flow, the details of which, will be discussed in the presentation.

References

[1] da Silva C. B., Hunt J. C. R., Eames I. and Westerwell J., (2014), Interfacial layers between regions of different turbulence intensity, *Annual Review of Fluid Mechanics, vol. 46, pp. 567-590.*

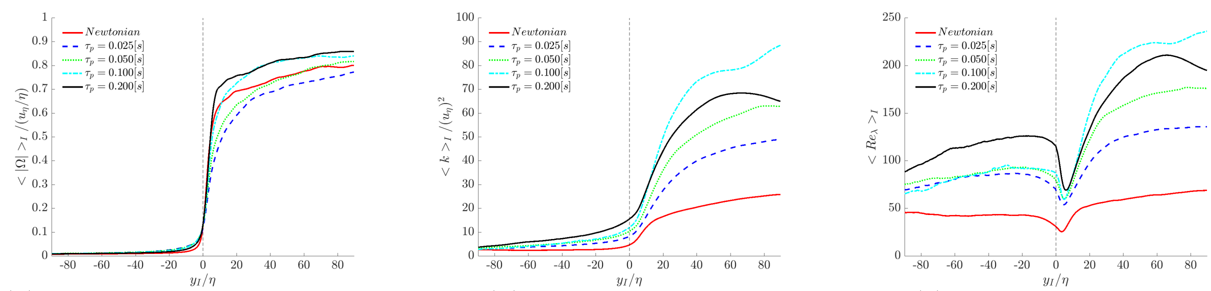
[2] G. Cocconi, G., De Angelis, E., Frohnapfel, B., Baevsky, M. and Liberzon, A., (2017), Small scale dynamics of a shearless turbulent/non-turbulent interface in dilute polymer solutions, *Physics of Fluids, vol. 29, pp. 075102.*

[3] Zecchetto, M., Silva, T. and da Silva, C.B., (2018), The scaling of the turbulent/non-turbulent interface at high Reynolds numbers, *Journal of Fluid Mechanics, vol. 843, pp. 156-179.*



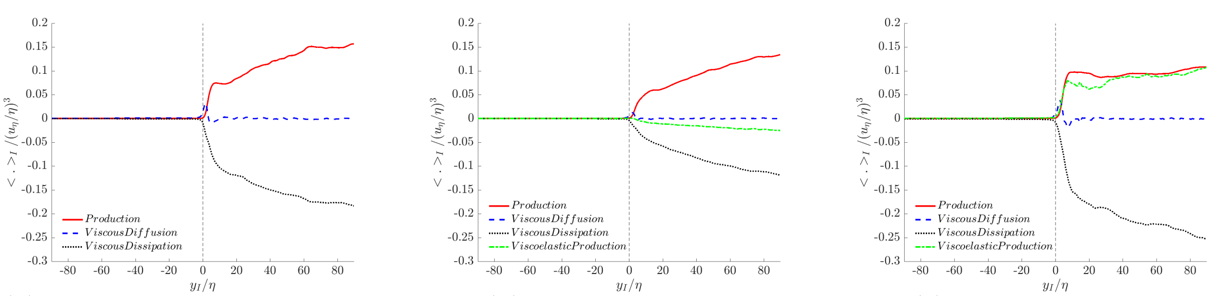
(a) (b) (c)

Figure 1: Top view of the irrotational boundary (IB) observed through iso-surfaces of vorticity magnitude corresponding to $\omega = \omega_{tr}$, for a Newtonian fluid (a), viscoelastic fluid with $\tau_p = 0.025$s, and a viscoelastic fluid with $\tau_p = 0.200$s (c).



(a) (b) (c)

Figure 2: Conditional mean profiles of enstrophy (a), turbulent kinetic energy (b), and Taylor based Reynolds number (c), for a Newtonian fluid, and viscoelastic fluids with $\tau_p = 0.025; 0.050; 0.100; 0.200$s.



(a) (b) (c)

Figure 3: Conditional enstrophy budgets for a Newtonian fluid (a), viscoelastic fluid with $\tau_p = 0.025$s, and a viscoelastic fluid with $\tau_p = 0.200$s (c).