Stretching of Polymers in Isotropic Turbulence: A Statistical Closure

D. Vincenzi[1] S. Jin[2] E. Bodenschatz[1,2]
L. R. Collins[2]

22 December 2006

[1] Max-Planck-Institut für Dynamik und Selbstorganisation, Am Fassberg 11/Turm 2, 37077 Göttingen, Germany
[2] Sibley School of Mechanical & Aerospace Engineering, Cornell University, Ithaca, NY 14853, USA

Abstract submitted to EE250

The dynamics of an isolated polymer molecule in a turbulent flow field is of both fundamental and practical significance. Turbulence provides a mixture of flow types (from rotation to strain) and the response of the polymer is very sensitive to the nature of the underlying flow. Moreover, turbulent flows vary rapidly in space and time, and this, combined with the elasticity of the polymer, produces very complex memory effects. The prime motivation to understand polymer-turbulence interactions is their potential use as drag reducing agents. Since the pioneering work of Toms [1], this technology is routinely used in oil pipelines to reduce pumping costs. The notion of using polymer additives to reduce the drag around ships and submarines has been around for decades, but has yet to be demonstrated on a full-scale system. Early approaches based on trial and error were not successful. Prediction of drag reduction on a complex surface moving at high Reynolds number requires generalized turbulence models (e.g., k–ϵ, Reynolds stress) capable of describing non-Newtonian fluids.

Direct numerical simulation (DNS) has recently emerged as an important tool for analyzing drag reduction in channel flows [2], boundary layers [3] and homogeneous turbulence [4]. The advantage DNS has over laboratory

experiments is that it yields information about the polymer orientation and the flow simultaneously, making it easier to understand the mechanism(s) of turbulent drag reduction and how they depend upon the polymer parameters. However, despite the successes of DNS, it is clear that it will not be a useful tool for designing large-scale systems at realistic Reynolds numbers.

We present a systematic closure approximation for the stretching term in the equation for the mean polymer conformation. This term plays an important role in non-Newtonian turbulence by establishing the mean stretch of the polymer due to turbulent fluctuations. The closure is obtained by assuming the velocity gradient in the Lagrangian frame of reference (i.e., frame of reference moving with the polymer molecule) is Gaussian and short-correlated. In that limit, the stretching term takes on an analytic form. We compare the result to stochastic simulations of the velocity gradient and find agreement in the limit as the correlation time approaches zero, as would be expected. For finite correlation times, the form of the closure approximation still appears to hold, but the coefficients must be adjusted. From simple fits, we obtain expressions for the coefficients as functions of the correlation time. Furthermore, we make comparisons with DNS of Newtonian turbulence with polymer and obtain optimized coefficients for this case. The model predictions and DNS are in very good agreement.

This work is in press in Phys. Rev. Lett.

References

[1] B. Toms, Proc. Int. Congr. Rheol. **2**, 135 (1948).

[2] R. Sureshkumar, A. N. Beris, and R. A. Handler, Phys. Fluids **9**, 743 (1997); T. Min et al., J. Fluid Mech. **486**, 213 (2003); P. K. Ptasinski et al., J. Fluid Mech. **490**, 251 (2003); Y. Dubief et al., J. Fluid Mech. **514**, 271 (2004).

[3] C. D. Dimitropoulos et al., Phys. Fluids **17**, 011705 (2005); J. S. Paschkewitz et al., J. Fluid Mech. **17**, 085101 (2005).

[4] T. Vaithianathan and L. R. Collins, J. Comp. Phys. **187**, 1 (2003); E. De Angelis et al., J. Fluid Mech. **531**, 1 (2003); A. Robert et al., J. Fluid Mech. (2006), in press.