Elasto-Inertial Turbulence in polymeric flows

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Collaborators

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Polymers and turbulence

Newtonian  Viscoelastic

Laminar

Transition

Turbulent

Re

$10^1$

$10^3$

$10^5$

Elastic turbulence

Early turbulence

Drag reduction

Elasto-Inertial Turbulence (EIT)

- State of small-scale turbulence
- Contributions from both elastic and inertial instabilities
- Observed over a wide range of Reynolds numbers
- Possibly state characterizing MDR
Polymers and turbulence

- Is drag reduction
  - a viscous and large-scale effect (Lumley)
  - an elastic and small-scale effect (de Gennes)
- What is the nature of EIT?
  - Relative contributions of elastic and inertial instabilities?
  - Characteristics of MDR?
  - Dynamical interactions between flow and polymers?
Polymers and turbulence

Newtonian

Viscoelastic

- Elastic turbulence
- Early turbulence
- Drag reduction

Approach
- Channel flow simulations
- FENE-P model
- Accurate numerics
- Transitional Reynolds numbers

Transition

Re

Laminar

Turbulent

Transition

10^1

10^3

10^5
Transitional viscoelastic flows

Channel flow simulations

Friction factor

- Departure from laminar state at $Re \sim 800$
- Smooth transition from laminar to MDR state
- Flow dynamics controlled by elastic and inertial instabilities
Transitional viscoelastic flows

Channel flow simulations

Friction factor

Re=1000, Wi⁺=24
- Not laminar
- Elastic contributions

Re=6000, Wi⁺=96
- Inertial & elastic contributions
- Turbulent?
- New state?

Isosurface of $Q_\alpha$ invariant
Transitional viscoelastic flows

Pipe flow experiment with PAAm solution

Friction factor

Results of numerical simulations are confirmed by experimental measurements

Samanta et al., PNAS 110(26), 2013
Qualitative flow behavior

Second invariant of the velocity gradient tensor: $Q_a = \frac{1}{2} (\Omega^2 - S^2)$
Qualitative flow behavior

Polymer extension \( (C_{ii} / L^2)^{1/2} \)

\[ \text{Re} = 1000 \]
\[ \text{Wi}^+ = 24 \]
Qualitative flow behavior

Second invariant of the velocity gradient tensor: $Q_a = \frac{1}{2} (\Omega^2 - S^2)$
Qualitative flow behavior

Polymer extension \( (C_{ii} / L^2)^{1/2} \)

\[ \text{Re} = 6000 \]
\[ Wi^+ = 96 \]
Typical structures

Contour of pressure and isolines of second invariant $Q_a$

- Train of cylindrical $Q_a$ structures of alternating sign
- On each side of sheet
- Associated with polymeric part of pressure
- Correlated with polymer body force $f_p$
Flow topology

EIT flow – Joint-PDF

- Change from shear flow \((R_a=Q_a=0)\) to mixed flow
- At low \(Re\), symmetric distribution around 2D flow \((R_a=0)\)
- At higher \(Re\), “teardrop” shape similar to Newtonian turbulence
Energy transfers

Turbulent kinetic energy budget

\[ \int P \, dV - \int \varepsilon \, dV - \int \Pi_e \, dV = 0 \]

Production
Dissipation
Transfer between elastic energy and turbulent kinetic energy

Transfers of turbulent kinetic energy
Re=1000, Wi+=24

Energy transfer from polymers to flow!

\[ P \int V - \int \varepsilon \, dV - \int \Pi_e \, dV = 0 \]
Energy spectrum

$E(\kappa_x)$

$\kappa_x^{-5/3}$

$\kappa_x^{-14/3}$

$\kappa_x^0$

$\kappa_x^2$

$\kappa_x^{-14/3}$ spectrum agrees well with elastic turbulence and hybrid simulation of Watanabe and Gotoh (JFM 2013)
Our current understanding

**Hyperbolic transport equation**
\[ \partial_t C + (\mathbf{u} \cdot \nabla) C = \ldots \]
- Formation of very thin sheets
- Trains of cylindrical structures

**Pressure Poisson equation**
\[ \nabla^2 p = 2Q_a - \frac{1-\beta}{\mathrm{Re}} \nabla \cdot (\nabla \cdot \mathbf{T}) \]
- Elliptical pressure redistribution of energy
- Excitation of extensional sheet flow

**Mixed extensional-shear flow**
... = \mathbf{C} (\nabla \mathbf{u}) + (\nabla \mathbf{u})^T \mathbf{C} - \mathbf{T}
- Increase of extensional viscosity (anisotropic)
- Anisotropic polymer body force

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Conclusion and future work

Key take-away messages

• EIT is a new state of small-scale turbulence driven by both elastic and inertial instabilities
• EIT could characterize MDR regime
• EIT explains seemingly contradictory phenomena in viscoelastic turbulence
• EIT provides support to de Gennes’ theory

Next steps

• Further characterize EIT
• Understand the exact mechanisms during transition process

Samanta et al., “Elasto-inertial turbulence”, PNAS 110(26), 2013
Terrapon, Dubief & Soria, Proceedings of the TSFP-8, 2013