Turbulent Boundary-Layer Drag Reduction

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Turbulent Boundary-Layer Drag Reduction

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This study was sponsored by DARPA, in the wake of ONR-sponsored JASON Study JSR-99-215 on Fast Transoceanic Transport (aka, "Fast Ships" study). The charge for this study is to focus on turbulent boundary-layer drag reduction, which was identified as necessary for transoceanic transport at high speeds, *i.e.*, at speeds U ^{3} 75 knots.

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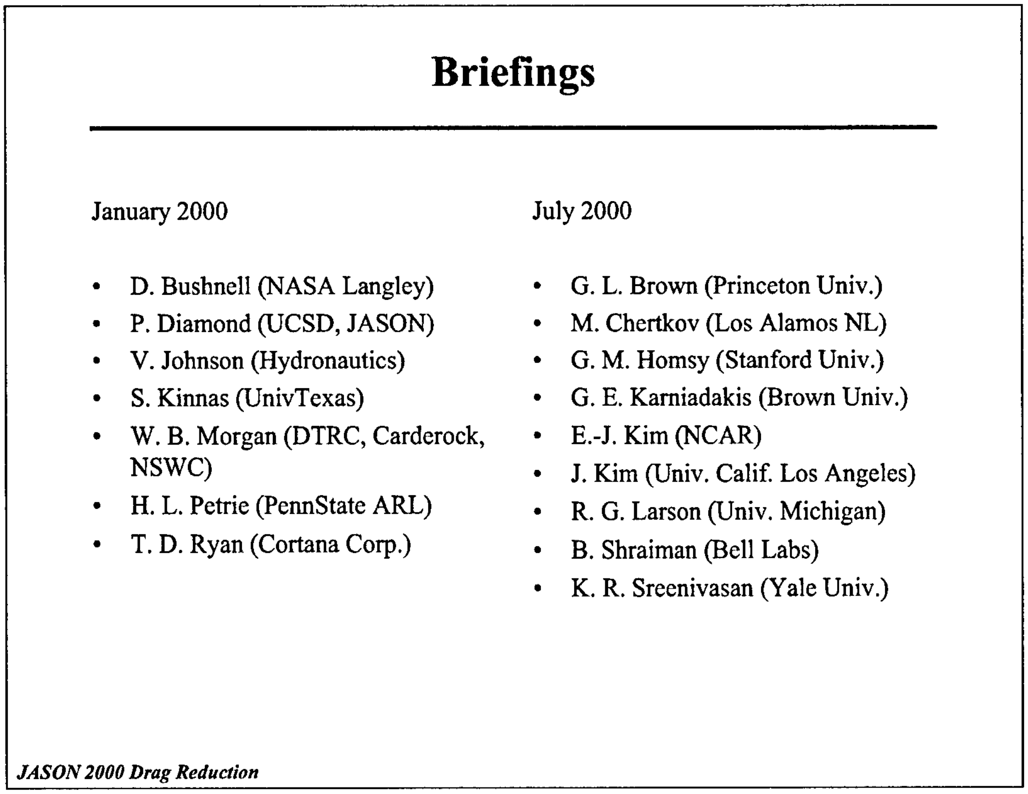
Abstract

This study was sponsored by DARPA, in the wake of last year's ONR-sponsored JASON Study JSR-99-215 on Fast Transoceanic Transport (aka, "Fast Ships" study).

The charge of this year's study was to focus on turbulent boundary-layer drag reduction, which was identified as necessary for transoceanic transport at high speeds, *i.e.*, at speeds $U \geq 75$ knots.



Briefings

January 2000

- D. Bushnell (NASA Langley)
- P. Diamond (UCSD, JASON)
- V. Johnson (Hydronautics)
- S. Kinnas (UnivTexas)
- W. B. Morgan (DTRC, Carderock, NSWC)
- H. L. Petrie (PennState ARL)
- T. D. Ryan (Cortana Corp.)

July 2000

- G. L. Brown (Princeton Univ.)
- M. Chertkov (Los Alamos NL)
- G. M. Homsy (Stanford Univ.)
- G. E. Karniadakis (Brown Univ.)
- E.-J. Kim (NCAR)
- J. Kim (Univ. Calif. Los Angeles)
- R. G. Larson (Univ. Michigan)
- B. Shraiman (Bell Labs)
- K. R. Sreenivasan (Yale Univ.)

G. Brown “Experiments on the Electromagnetic Control of Turbulent Flow.”

D. Bushnell “ ‘Designer Fluid Mechanics’ and ‘Fast Ship’.”

M. Chertkov “Polymer Stretching by Turbulence and Elastic Turbulence Theory.”

P. H. Diamond “Elasticity in Turbulence: Polymer Drag Reduction in Turbulent Flow.”

G. M. Homsy “High Reynolds Number Viscoelastic Shear Layers.”

V. Johnson “Lift/Drag measurements on a ‘surfing’ foil.”

G. E. Karniadakis “Drag reduction by Means of Transverse Traveling Waves.”

E.-J. Kim “Suppression of Chaos and Momentum Transport in MHD Flows.”

J. Kim “Active Control of Turbulent Boundary Layers for Drag Reduction.”

R. Larson “Single-molecule hydrodynamics of polymer molecules.”

W. B. Morgan “Hydrodynamic Facilities and Model Testing with Emphasis on High-Speed Ships.”

H. L. Petrie “Fast Ship Drag Reduction.”

T. D. Ryan “Engineering of Drag Reduction Systems for Marine Vehicles.”

B. Shraiman “Scalar turbulence.”

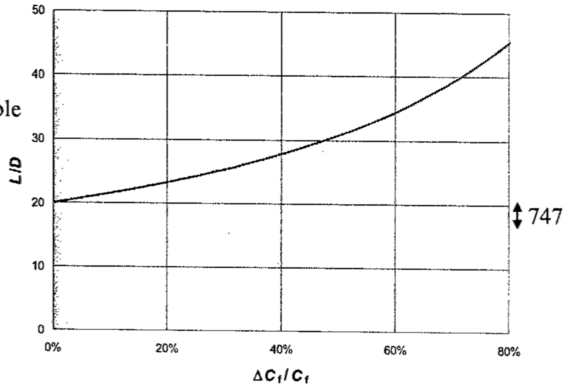
K. R. Sreenivasan “Remarks on Turbulent Drag Reduction,”

Previous JASON Work — I

PED *et al.* 1999 "Fast Ships: Hydrodynamics of Fast Ocean Transport," JSR-99-215.

- Feasibility study of transport vessels characterized by
  - high-speed: 75 knot +
  - long-range: 10 knm
  - Moderate displacement: 10 ktons

➤ This requires (system) $L/D \approx 40$
  - $L/D \approx$ 18-20 achievable today
  - Roughly 70% of drag attributable to boundary-layer friction
  - $L/D \approx 40$ requires $\approx \times$3-4 reduction in BL drag.

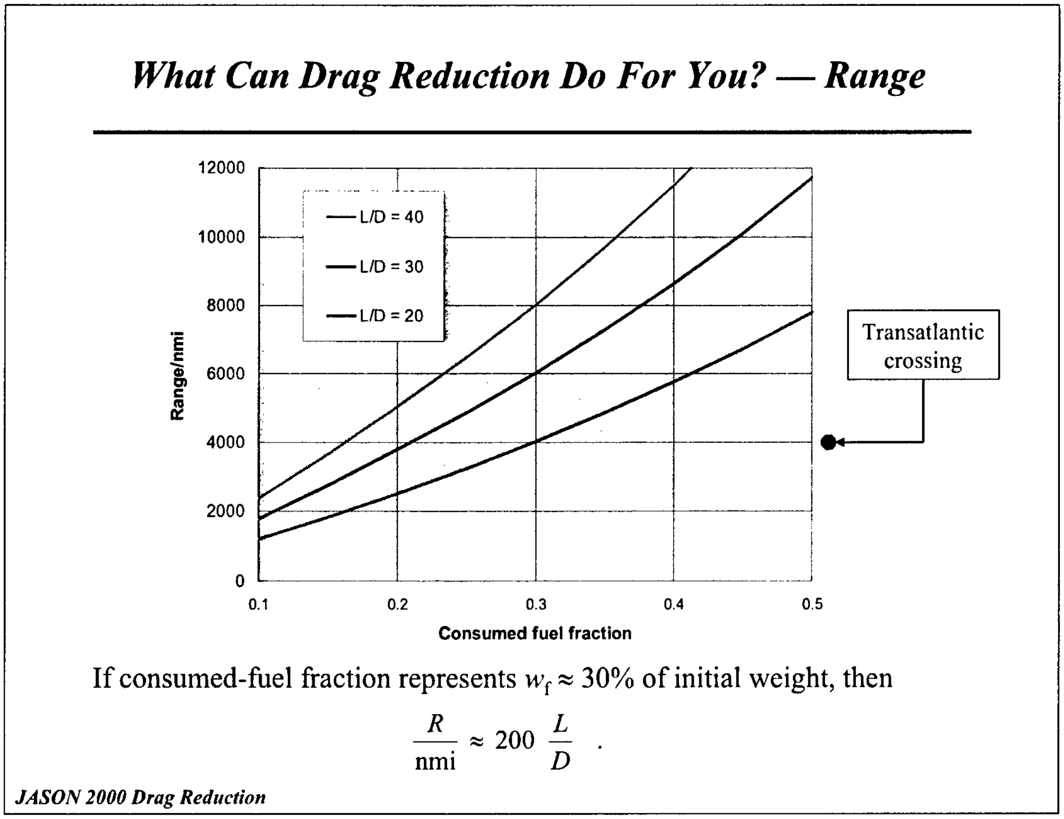


The previous JASON Study (JSR-99-215) on fast transoceanic transport considered a high-span ($b \sim 65$ m), dual-hydrofoil-borne ship as a notional design as perhaps the only viable choice at the speeds indicated. It concluded that a system lift-to-drag ratio of $L/D \approx 40$ was necessary to approach the desired specifications of a fast Army transport.

Economic-viability issues, *e.g.*, that a commercial carrier, such as FedEx, should be able to operate a fleet of such vessels also argue for a high-L/D vessel. That was also a consideration last year's study was invited to consider.

The figure plots L/D, against percentage skin-friction drag reduction, for a ship that achieves $L/D \approx 20$ without drag reduction, assuming that the unreduced skin friction is 70% of the total drag.

$L/D \approx 20$, achievable with high optimization of conventional technology, is still an ambitious goal. The L/D for a Boeing 747 — a very capable flyer — is in the range of 16-18 and included as a reference.



What Can Drag Reduction Do For You? — Range

If consumed-fuel fraction represents $w_f \approx 30\%$ of initial weight, then

$$\frac{R}{\text{nmi}} \approx 200\,\frac{L}{D}\ .$$

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The range relation plotted derives from the Breguet equation (*e.g.*, JSR-99-215)

$$\frac{R}{\text{n.mi}} \approx 322\,\frac{\eta_P\, L/D}{c_{\text{fuel}} / [\text{lb}/\text{HP}\cdot\text{hr}]}\ \ln\left(1-w_{\text{fuel}}\right)^{-1}$$

in which,

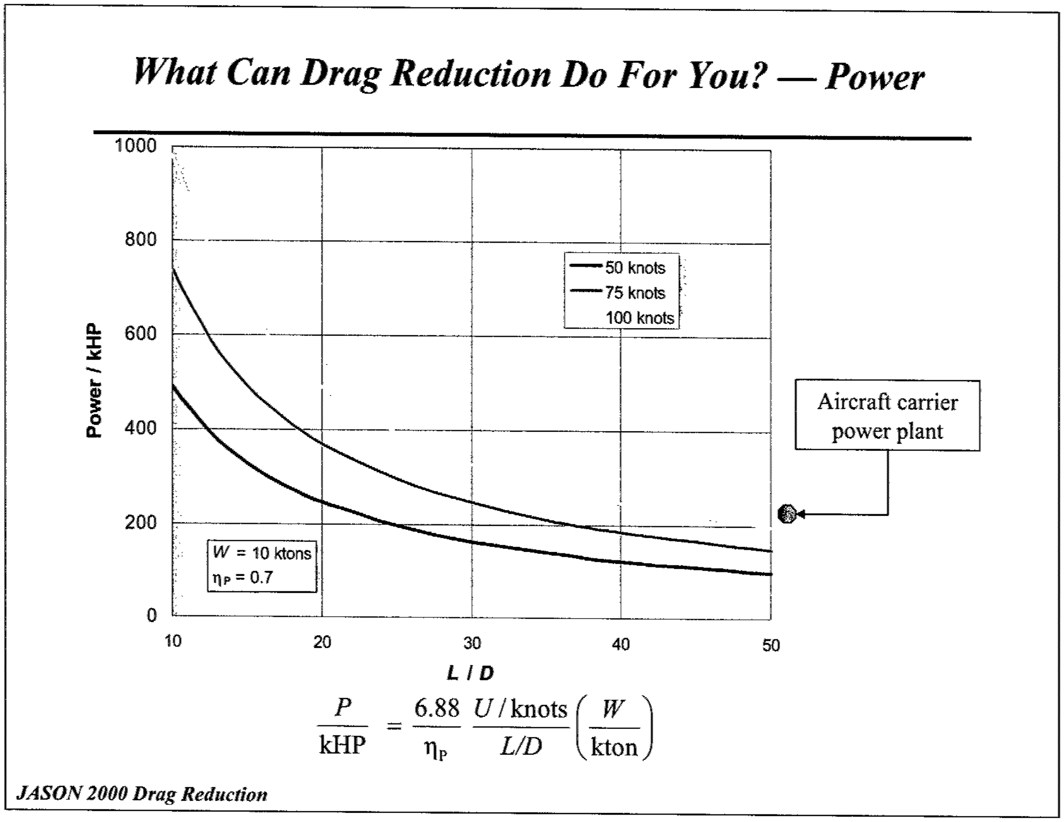
$\eta_P \approx 0.7$ is the propulsion efficiency (plant HP to propulsive HP),

L/D is the (average) lift-to-drag ratio (treated as a constant),

w_{fuel} is the initial displacement (weight) fraction allocated to fuel,

and

$c_{\text{fuel}} \approx 0.4$ lbm/HP-hr is the (reciprocal) of the fuel energy content per unit mass.



What Can Drag Reduction Do For You? — Power

$$\frac{P}{\text{kHP}} = \frac{6.88}{\eta_P}\,\frac{U/\text{knots}}{L/D}\left(\frac{W}{\text{kton}}\right)$$

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The expression below the figure and the corresponding plots express the required (plant) power (force × speed), including the consequence of the propulsion efficiency, η_P, in kHP.

If high speed is to be attained, it is the power requirements that dictate the high *L*/*D* values mentioned above and preclude, as a practical matter, contemplating speeds in excess of 75 knots.

Previous JASON Work — II

- P. Diamond *et al.* 1992 “Drag Reduction by Polymer Additives,” JSR-89-720.
  - ➤ Extending Bird *et al.* (1987), proposed a coupled tensor-field description of the local elastic-elongation response of a dilute polymer solution to
    - hydrodynamic stretch (strain rate),

    opposed by
    - the characteristic relaxation time of stretched polymer “dumb-bells”
  - ➤ Noted formal analogy between coupled hydrodynamic and polymer-stretch fields with MHD flows.
  - – Did not address drag-reduction mechanism(s).

- C. Callan and K. Case 1981 “Drag Reduction and Adaptive Boundary Conditions,” JSR-81-17.
  - – Boundary-layer stability and potential increases of stability margins.

The Diamond *et al.* (1992) JSR-89-720 report provided an important summary of ideas at the time, as well as a significant impetus and guidance for this year’s study. It identifies the mechanisms and dynamics that couple polymer-elastization fields and turbulence.

The Callan & Case (1981) JSR-81-17 study focused on hydrodynamic stability and transition out of the laminar state and, as a consequence, is less germane to the high-speed regime of interest in the present context.

Three- to Four-Fold Drag-Reduction?

- Technologies with demonstrated ×3-4 drag-reduction potential
  - High-MW polymers
  - Surfactants (surface-active agents)
  - Microbubbles ($d_b < 50\ \mu\text{m}$)
  - Air/vapor films

- Other technologies considered
  - Electromagnetic Turbulence Control (EMTC)
  - Active (feedback) control

- Issues
  - Momentum transport
  - Drag-reduction-power expended *vs*. propulsive-power saved

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In addition to the four technologies listed at the top that meet the ×3-4 drag-reduction criterion, two other technologies were considered.

Electromagnetic Turbulence Control (EMTC) was cited by Du & Karniadakis (2000, *Science*) in their computer simulations of moderate-*Re* boundary-layer flows as capable reducing drag by factors comparable to the values of interest here, with small required powers. John Kim, in his July 2000 briefing to us (also Kim 2000), agreed with the drag-reduction findings by Du & Karniadakis, but offered a differing estimate of power requirements for a given drag-reduction level. Resolving this disagreement was one of the issues examined as part of this year's study.

Active (feedback) control technology has also recently claimed large drag-reduction benefits, based on computer simulations.

Issues addressed included mechanisms for momentum transport and turbulent boundary-layer drag reduction, as well as issues of efficiency. Efficiency here means the ratio of power saved by drag reduction to power expended to achieve it.

Momentum For A Continuum Material

- Momentum conservation for a differential volume element of a continuum substance (Cauchy's equation)

$$\rho \frac{\mathbf{Du}}{\mathrm{D}t} = \rho \mathbf{f} - \nabla p + \nabla \cdot \boldsymbol{\tau}$$

where,

- $\rho = \rho(\mathbf{x},t)$ is the density field,
- $\mathbf{u} = \mathbf{u}(\mathbf{x},t)$ is the velocity field,
- $\mathrm{D}/\mathrm{D}t \equiv \partial/\partial t + \mathbf{u} \cdot \nabla$ (convective derivative),
- $\mathbf{f} = \mathbf{f}\,(\mathbf{x},t)$ is any body-force field (*e.g.*, E&M Lorentz force),
- $p = p(\mathbf{x},t)$ the pressure field, and
- $\boldsymbol{\tau} = \boldsymbol{\tau}(\mathbf{x},t)$ the total stress tensor field
  - $\tau_{ij} = \tau_{ji}$ for isotropic fluid

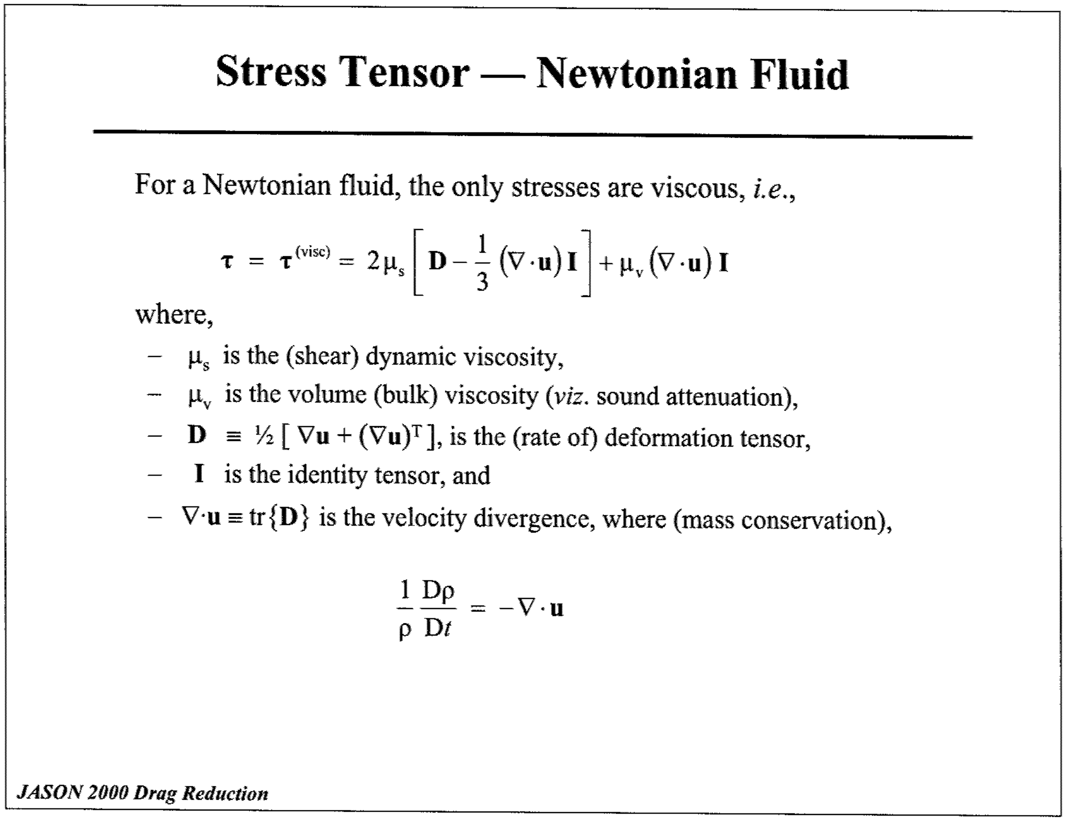
In considering drag- and momentum-transport issues, the general (Cauchy) equation should be used, in which the form of the body forces and/or stress tensor can be defined as appropriate to capture imposed external body forces as well as modifications to the flow stress field as a consequence changes in the rheology of the fluid. In this form, it applies to the motion of both Newtonian and non-Newtonian fluids.

D/D*t* denotes the convective (Lagrangian) derivative and be expressed in terms of local (Eulerian) time and space derivatives, *i.e.*,

$$\frac{\mathrm{D}}{\mathrm{D}t} \equiv \frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla \quad .$$

As expressed in the equation in the frame, **f** is a body force field and has units of acceleration, *e.g.*, gravity.

For an isotropic fluid, the stress tensor must be symmetric. Isotropy may or may not be valid as an assumption for a solution of long-stranded molecules, such as high molecular-weight polymers.



Stress Tensor — Newtonian Fluid

For a Newtonian fluid, the only stresses are viscous, *i.e.*,

$$\boldsymbol{\tau} \; = \; \boldsymbol{\tau}^{(\mathrm{visc})} = 2\mu_s \left[\mathbf{D} - \frac{1}{3} (\nabla \cdot \mathbf{u}) \, \mathbf{I} \right] + \mu_v (\nabla \cdot \mathbf{u}) \, \mathbf{I}$$

where,

- μ_s is the (shear) dynamic viscosity,
- μ_v is the volume (bulk) viscosity (*viz.* sound attenuation),
- $\mathbf{D} \equiv \frac{1}{2} [\nabla \mathbf{u} + (\nabla \mathbf{u})^T]$, is the (rate of) deformation tensor,
- $\mathbf{I}$ is the identity tensor, and
- $\nabla \cdot \mathbf{u} \equiv \mathrm{tr}\{\mathbf{D}\}$ is the velocity divergence, where (mass conservation),

$$\frac{1}{\rho} \frac{\mathrm{D}\rho}{\mathrm{D}t} \; = \; -\nabla \cdot \mathbf{u}$$

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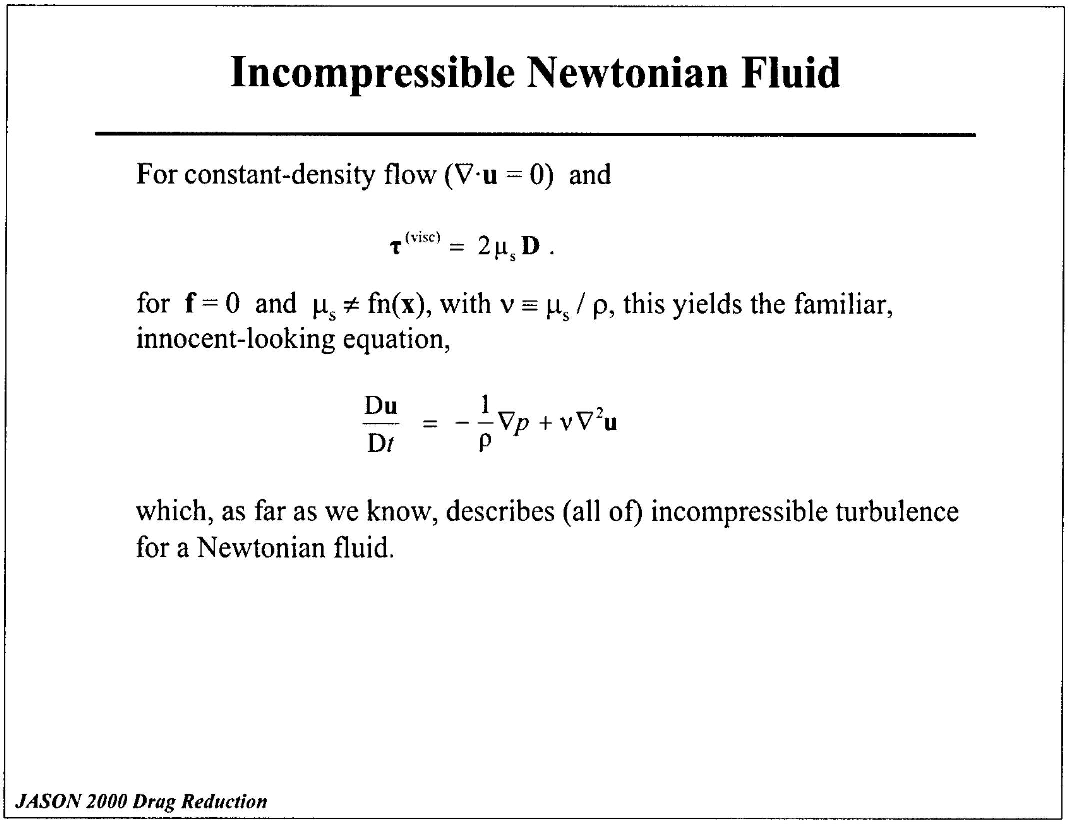
This expression for the stress, a function of two viscosity coefficients, defines a simple (single-component) Newtonian fluid. The shear and bulk viscosity coefficients, μ_s and μ_v [Pa·s in MKS], are thermodynamic variables, and functions of the *fluid* and not the *flow*.

In Cartesian-component form, the deformation tensor, **D**, and velocity divergence (dilatation), $\nabla \cdot \mathbf{u}$, are given by,

$$D_{ij} \; = \; \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial xi} \right) \quad , \quad \nabla \cdot \mathbf{u} \; = \; \sum_i \frac{\partial u_i}{\partial x_i} \quad .$$

In the context of Fast Ships, including the contribution of dilatation ($\nabla \cdot \mathbf{u}$) is necessary in the study of microbubbles, which increase compressibility and decrease the speed of sound substantially, leading to significant compressibility effects at the speeds of interest ($U \geq 35$ m/s). This will be discussed later.



Incompressible Newtonian Fluid

For constant-density flow ($\nabla \cdot \mathbf{u} = 0$) and

$$\boldsymbol{\tau}^{(\text{visc})} = 2 \mu_s \mathbf{D} \, .$$

for $\mathbf{f} = 0$ and $\mu_s \neq \text{fn}(\mathbf{x})$, with $\nu \equiv \mu_s / \rho$, this yields the familiar, innocent-looking equation,

$$\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{u}$$

which, as far as we know, describes (all of) incompressible turbulence for a Newtonian fluid.

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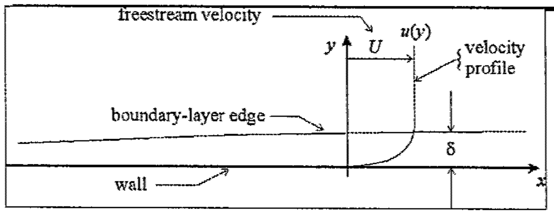
In the context of Fast Ships, for drag-reduction not based on microbubbles or air/vapor films endowed with significant dynamic-pressure variations, dilatation is negligible and the incompressible-flow equations can be used.

Boundary-Layers — Steady Flows



$$\mathbf{x} = (x, y), \quad \mathbf{u} = (u, v),$$

$$\frac{\delta}{x} \ll 1 \quad \text{and} \quad \frac{v}{u} \ll 1,$$

$$u(y) \to U\,, \quad \text{for } y \geq \delta\,.$$

Boundary-layer approximation (Prandtl 1906):

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = U\frac{\mathrm{d}U}{\mathrm{d}x} + \frac{1}{\rho}\frac{\partial \tau}{\partial y}$$

$$p(\mathbf{x}) = p(x)$$

$$u(x,0) = v(x,0) = 0\,, \quad u(x,\infty) = U$$

Pressure ≠ fn(y) and can be estimated using Bernoulli equation and variation in the freestream velocity, U. For a Newtonian fluid:

$$\frac{1}{\rho}\frac{\partial \tau}{\partial y} \approx \nu\frac{\partial^2 u}{\partial^2 y}\,; \quad \nu \equiv \frac{\mu}{\rho}.$$

with,

$$\tau_{\text{wall}} = \mu\left(\frac{\partial u}{\partial y}\right)_{y=0}.$$

For laminar boundary layers (Blasius-equations solutions), with x the wetted length (upstream streamwise extent of growing boundary layer), we have:

$$\frac{\delta}{x} = \frac{5.0}{Re_x^{1/2}}$$

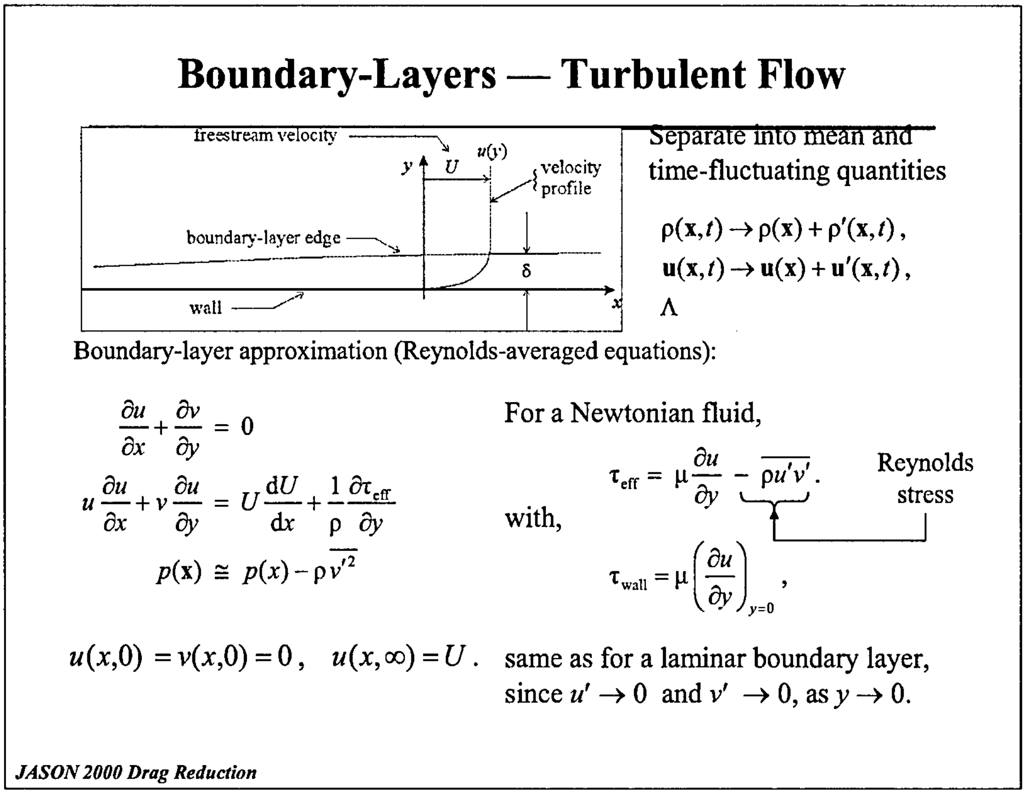
$$\frac{\delta_1}{x} \equiv \frac{1}{x}\int_0^\infty \mathrm{d}y\left(1 - \frac{u}{U}\right) = \frac{1.721}{Re_x^{1/2}} \cong 0.34\frac{\delta}{x} \quad \text{(displacement thickness)}$$

$$\frac{\delta_2}{x} \equiv \frac{1}{x}\int_0^\infty \mathrm{d}y\,\frac{u}{U}\left(1 - \frac{u}{U}\right) = \frac{0.664}{Re_x^{1/2}} \cong 0.13\frac{\delta}{x} \quad \text{(momentum thickness)}$$

$$C_\mathrm{f} \equiv \frac{\tau_\mathrm{w}}{\rho U^2/2} = \frac{\delta_2}{x} = \frac{0.664}{Re_x^{1/2}} \quad \text{(skin - friction coefficient)}$$

$$C_D(L) \equiv \frac{1}{L}\int_0^L \mathrm{d}x\, C_\mathrm{f}(x) = \frac{1.328}{Re_x^{1/2}}, \quad \text{with}$$

$$Re_x \equiv \frac{\rho\, U\, x}{\mu}\ .$$



Boundary-Layers — Turbulent Flow

Separate into mean and time-fluctuating quantities

$$\rho(\mathbf{x},t)\rightarrow\rho(\mathbf{x})+\rho'(\mathbf{x},t),$$
$$\mathbf{u}(\mathbf{x},t)\rightarrow\mathbf{u}(\mathbf{x})+\mathbf{u}'(\mathbf{x},t),$$
$$\Lambda$$

Boundary-layer approximation (Reynolds-averaged equations):

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=U\frac{\mathrm{d}U}{\mathrm{d}x}+\frac{1}{\rho}\frac{\partial\tau_{\mathrm{eff}}}{\partial y}$$

$$p(\mathbf{x})\cong p(x)-\rho\overline{v'^2}$$

$$u(x,0)=v(x,0)=0,\quad u(x,\infty)=U.$$

For a Newtonian fluid,

$$\tau_{\mathrm{eff}}=\mu\frac{\partial u}{\partial y}-\underbrace{\overline{\rho u'v'}}_{\text{Reynolds stress}}.$$

with,

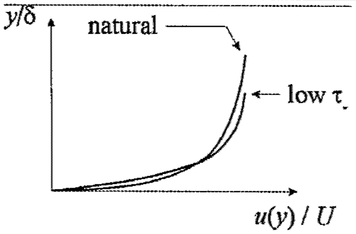
$$\tau_{\mathrm{wall}}=\mu\left(\frac{\partial u}{\partial y}\right)_{y=0},$$

same as for a laminar boundary layer, since $u'\rightarrow 0$ and $v'\rightarrow 0$, as $y\rightarrow 0$.

Phenomenologically, in terms of their action on mean flow profiles, the cross-stream correlations of the turbulent velocity fluctuations can be viewed as contributing an additional stress, dubbed the *Reynolds stress*.

For flow of a Newtonian fluid, the shear-stress at the wall, τ_w, has the same form for steady (laminar) and turbulent flow, because fluctuations vanish as the wall is approached, driving Reynolds stresses to zero.

Boundary-Layers — Velocity Profiles



$$\tau_w = \mu\left(\frac{\partial u}{\partial y}\right)_{y=0} \quad , \quad u_\tau \equiv \sqrt{\tau_w/\rho} = U\sqrt{C_f/2};$$

$$u^+ \equiv \frac{u}{u_\tau} = \frac{y u_\tau}{\nu} \equiv y^+ \,, \quad \text{for } y^+ \geq 5$$

$$u^+ \cong \frac{1}{\kappa}\ln y^+ + B + \frac{\Pi}{\kappa} f(y/\delta) \;, \quad y^+ \geq 30 \,, \text{with}$$

$$\kappa \cong 0.4 \,, B \cong 5.0-5.2, \;\; \Pi = \text{fn}(Re_\delta); \;\; \text{smooth walls.}$$

- Coupling of τ_w to velocity profile applies to Newtonian and non-Newtonian fluid flow, if other stresses vanish at the wall.
- Changes in shear-stress at the wall linked to changes in boundary-layer velocity profile.
  - Potentially, a rock and a hard place: in decreasing τ_w one can produce unstable BL velocity profiles
- An integral relation between BL velocity profiles and shear stress at the wall can be expressed, for general fluids, by extending the T. von Kármán boundary-layer momentum integral.

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For $Re_{\delta 1} > 10^4$, or so, $\Pi \approx 0.62$. For a smooth wall, the skin-friction coefficient can be approximated by the Prandtl-Kármán relation,

$$\frac{1}{\sqrt{C_f}} \cong 4.0 \; \log_{10}\left[Re_x\sqrt{C_f}\right] - 5.6$$

or, the explicit, modified (JSR-99-215) Hama (1954) relation,

$$\frac{1}{\sqrt{C_f}} \cong 3.44 \; \log_{10} Re_x \; - \; 5.6$$

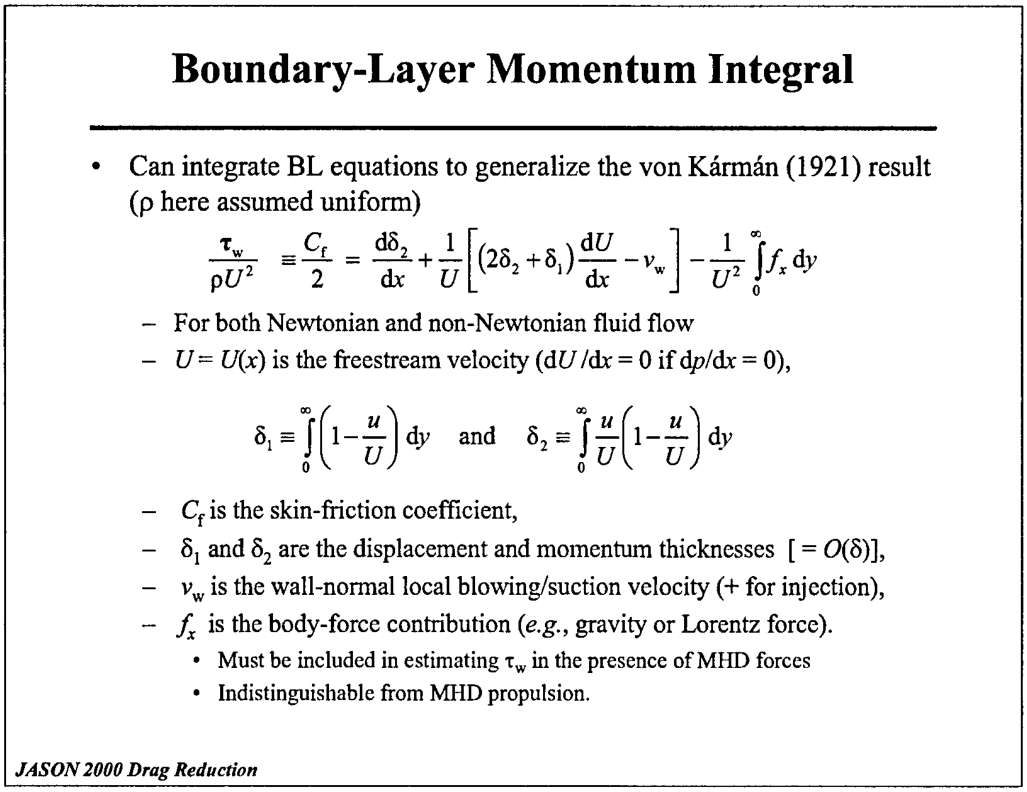
Turbulent boundary-layer thickness scales are given by,

$$\frac{\delta}{x} \cong \frac{0.16}{Re_x^{1/7}}$$

$$\frac{\delta_1}{\delta} \cong \alpha\left(\frac{u_\tau}{U}\right) = \alpha\sqrt{C_f/2} \quad , \quad \alpha \cong 3.6\,;$$

$$\frac{\delta_2}{\delta} \cong \alpha\left(\frac{u_\tau}{U}\right) - \beta\left(\frac{u_\tau}{U}\right)^2 \quad , \quad \beta \cong 6.8\,\alpha;$$

$$\frac{\delta_1}{\delta_2} \cong \frac{1}{1-6.8\sqrt{C_f/2}} \quad .$$



Boundary-Layer Momentum Integral

- Can integrate BL equations to generalize the von Kármán (1921) result (ρ here assumed uniform)

$$\frac{\tau_w}{\rho U^2} \equiv \frac{C_f}{2} = \frac{d\delta_2}{dx} + \frac{1}{U}\left[(2\delta_2 + \delta_1)\frac{dU}{dx} - v_w\right] - \frac{1}{U^2}\int_0^\infty f_x \, dy$$

  - For both Newtonian and non-Newtonian fluid flow
  - $U = U(x)$ is the freestream velocity ($dU/dx = 0$ if $dp/dx = 0$),

$$\delta_1 \equiv \int_0^\infty \left(1 - \frac{u}{U}\right) dy \quad \text{and} \quad \delta_2 \equiv \int_0^\infty \frac{u}{U}\left(1 - \frac{u}{U}\right) dy$$

  - C_f is the skin-friction coefficient,
  - δ_1 and δ_2 are the displacement and momentum thicknesses [$= O(\delta)$],
  - v_w is the wall-normal local blowing/suction velocity (+ for injection),
  - f_x is the body-force contribution (*e.g.*, gravity or Lorentz force).
    - Must be included in estimating τ_w in the presence of MHD forces
    - Indistinguishable from MHD propulsion.

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The result derived is, basically, the same as the von Kármán (1921) boundary-layer integral, except that τ_w, here, is the stress as it appears in the Cauchy equation (Slide 9) and the effect of the body force (acceleration) field, f_x, is explicitly included.

In the case of non-Newtonian fluid flow and/or in the presence of imposed body (*e.g.*, Lorentz) forces, it is important to include (measure) the total τ_w not just the Newtonian contribution.

The effect of injection/suction velocity at the wall, v_w, is noted. Injection can be seen to *decrease* shear stress at the wall. However, fluid injected with zero stream-wise momentum (as assumed here) will acquire momentum from the freestream, contributing a Reynolds stress and increasing drag.

It is important to perform integrated drag-reduction measurements. In the case of Lorentz, or other spatially inhomogeneous force fields, shear-stress at the wall can be driven to zero locally, even as there may be an overall drag *increase*. Results from some measurements we reviewed suffer from this difficulty, rendering their assessment problematical.

Momentum, Body Forces, And Stresses

Momentum transport can be altered by:

- Additional body forces
  - Electromagnetic: $\rho \mathbf{f} \rightarrow \rho \mathbf{f} + \mathbf{j}_e \times \mathbf{B}$,
    where
    - $\mathbf{j}_e$ is the electric-current density, and
    - $\mathbf{B}$ is the magnetic field
- Changing/adding-to the stress field:

$$\boldsymbol{\tau}_{\mathrm{eff}} = \boldsymbol{\tau}^{(\mathrm{visc})} - \overline{\rho \mathbf{u}'\mathbf{u}'} + \boldsymbol{\tau}^{(1)} + \boldsymbol{\tau}^{(2)} + \Lambda$$

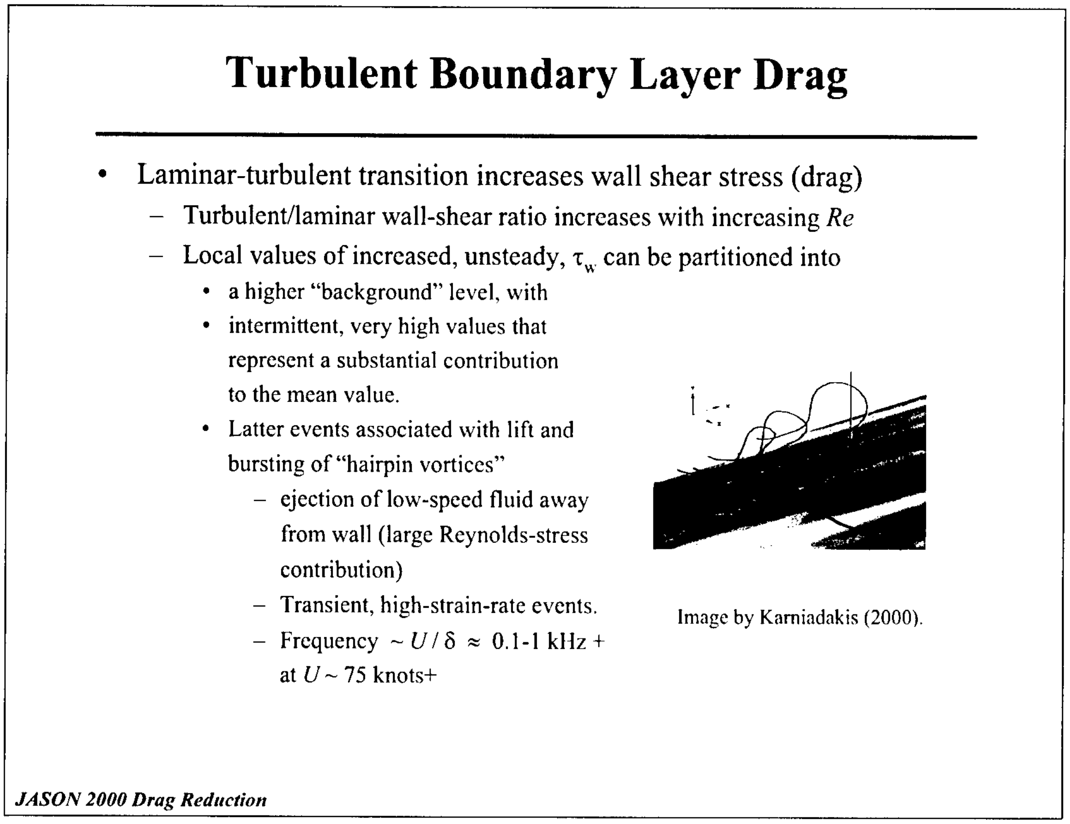
where changes in the first two and/or additional stresses can be the result of changes in the fluid rheological properties, *e.g.*, via

  - polymers
  - surfactants
  - microbubbles
  - …

Body forces and additional (non-Newtonian) stress contributions can oppose Reynolds-stress contributions and lead to drag reduction.

In the case of polymers, surfactants, and microbubbles there can be changes to the Newtonian stress, through changes in the shear viscosity, μ. In comparing experiments, it is important to distinguish between changes in drag coefficients stemming from changes in (local) *Re* from those that arise from changes owing to changes in rheological behavior. At the low concentrations that high-MW polymers are typically employed, the change in the Newtonian shear viscosity is small. This is not the case for surfactants, however, that are used at, typically, ×10 wppm higher concentrations than high-MW polymers.

Care should be exercised in assessing experimental results to make sure that data are correctly parameterized as a function of additive concentration, *i.e.*, referenced to the correct (modified) Newtonian shear viscosity, in each case.



Turbulent Boundary Layer Drag

- Laminar-turbulent transition increases wall shear stress (drag)
  - Turbulent/laminar wall-shear ratio increases with increasing *Re*
  - Local values of increased, unsteady, τ_w can be partitioned into
    - a higher "background" level, with
    - intermittent, very high values that represent a substantial contribution to the mean value.
    - Latter events associated with lift and bursting of "hairpin vortices"
      - ejection of low-speed fluid away from wall (large Reynolds-stress contribution)
      - Transient, high-strain-rate events.
      - Frequency $\sim U / \delta \approx$ 0.1-1 kHz + at $U \sim$ 75 knots+

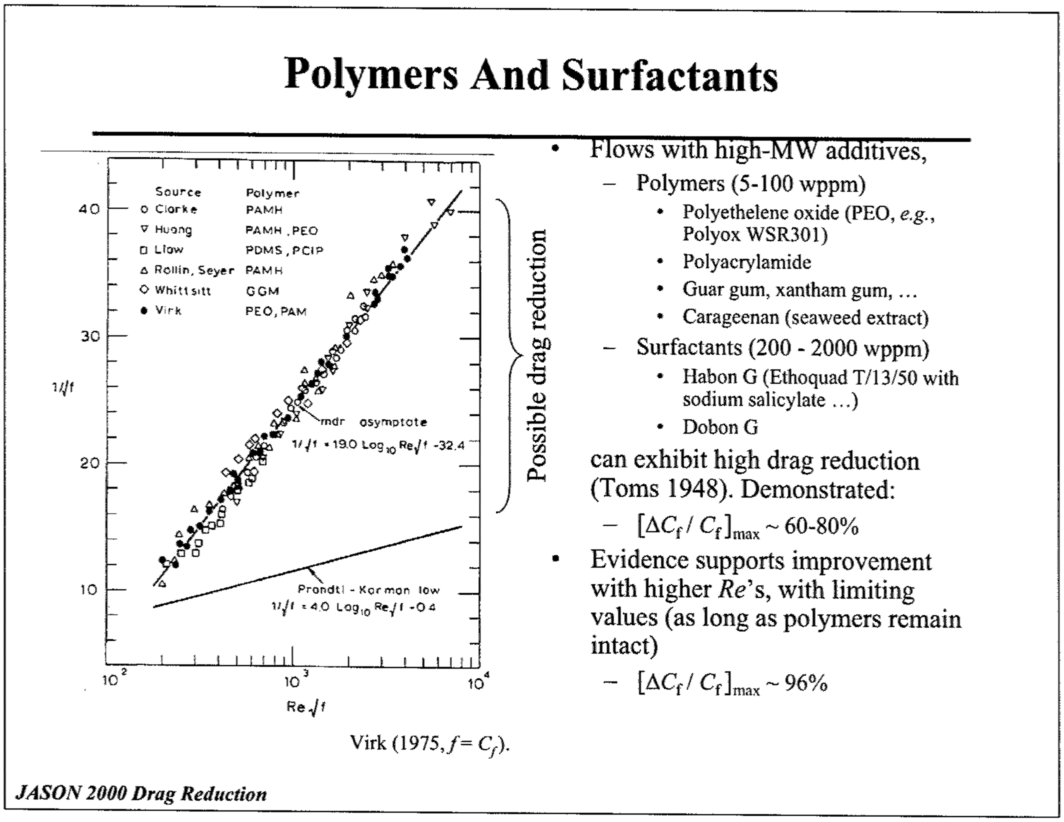
Image by Karniadakis (2000).

JASON 2000 Drag Reduction

The structure of near-wall turbulent-boundary layer flows and identifiable "events" responsible for momentum transport and drag are subjects of continuing research. "Hair-pin" vortex-ejection events, which bring near-wall, low-speed fluid away from the wall have the correct correlation to contribute to Reynolds stress. Such events can be viewed as an instability of the counter-rotating, streamwise vortex structures, which are spaced by $\lambda^+ \equiv \lambda\, u_\tau / \nu \approx 100$ and centered at $y^+ \equiv y\, u_\tau / \nu = 20$-30 (Blackwelder and Eckelmann 1979), and represent intermittent, energetic, high-strain-rate events.

The route to hair-pin ejection events may be akin to that of the Crow instability (1970), which is responsible for interrupting the lift-induced counter-rotating trailing vortex pairs (contrails) by pairing interactions behind aircraft. In the case of the wall-adjoining counter-rotating vortex system, the self-induction plus wall-mirror effects will result in a lifting of vortex lines, as indicated in the computed image by Karniadakis in the frame.

It is plausible that polymers and surfactants act by resisting the transient elongation (extensional strain rate) associated with such a motion, decreasing the frequency of such events and drag thereby. Such resistance to extensional strain is akin to the resistance to bending of magnetic-field lines in MHD flow.



Polymers And Surfactants

Virk (1975, $f = C_f$).

- Flows with high-MW additives,
  - Polymers (5-100 wppm)
    - Polyethelene oxide (PEO, *e.g.*, Polyox WSR301)
    - Polyacrylamide
    - Guar gum, xantham gum, …
    - Carageenan (seaweed extract)
  - Surfactants (200 - 2000 wppm)
    - Habon G (Ethoquad T/13/50 with sodium salicylate …)
    - Dobon G

  can exhibit high drag reduction (Toms 1948). Demonstrated:
  - $[\Delta C_f / C_f]_{\max} \sim 60\text{-}80\%$
- Evidence supports improvement with higher *Re*'s, with limiting values (as long as polymers remain intact)
  - $[\Delta C_f / C_f]_{\max} \sim 96\%$

JASON 2000 Drag Reduction

Taking the ratio of the Prandtl-Kármán friction-coefficient relation and the maximum-drag-reduction asymptote suggested by Virk (1975), we have,

$$\max \left(\sqrt{C_{\mathrm{f}}}\right)_{\mathrm{pol}} \approx \frac{4.0}{19} \left(\sqrt{C_{\mathrm{f}}}\right)_0 \quad \Rightarrow \quad \max \left(C_{\mathrm{f}}\right)_{\mathrm{pol}} \approx 0.04 \left(C_{\mathrm{f}}\right)_0 \quad ,$$

for large *Re*'s (zero subscripts denote "natural" skin-friction drag coefficients). However, at fixed flow geometry, the maximum *Re* where drag-reduction benefits can be expected will be limited by polymer degradation at the correspondingly high strain rates.

A somewhat higher drag-reduction asymptote has been reported for surfactants (Zakin *et al.* 1996).

Polymers: Dynamics

- Polymers are chains of $N \approx 10^4$ - 10^5 monomer 'beads' that coil to produce a cluster of size (radius of gyration), $R_g \approx l\, N^{0.6} \sim 80$ nm; l is the link size.
- Phenomenological (convected Jeffreys, or Oldroyd-B 1950) models have introduced convected stress fields to describe viscoelastic behavior
  - Most analyses to date based on these and derivative equations
- The coiled cluster is elastic (wants to stay quasi-spherical),
  - with a free energy of $F = ½\, \kappa_H R^2$
    - $\kappa_H = k_B T / R_g^2$ is the effective Hookean (entropic) spring constant, and
    - k_B the Boltzman constant.
  - and a viscoelastic relaxation mechanism (Zimm)

$$\underbrace{\gamma_S}_{\text{Stokes drag}}\left(\frac{d\mathbf{q}}{dt} - \mathbf{q}\cdot\nabla\mathbf{u}\right) = \underbrace{-\kappa_H\mathbf{q}}_{\text{elastic force}} + \underbrace{\varepsilon_T}_{\text{thermal excitation}} \Rightarrow \underbrace{\omega_Z}_{\text{Zimm frequency}} \equiv \frac{\kappa_H}{\gamma_S} \cong \frac{k_B T}{6\pi\mu R_g^3}$$

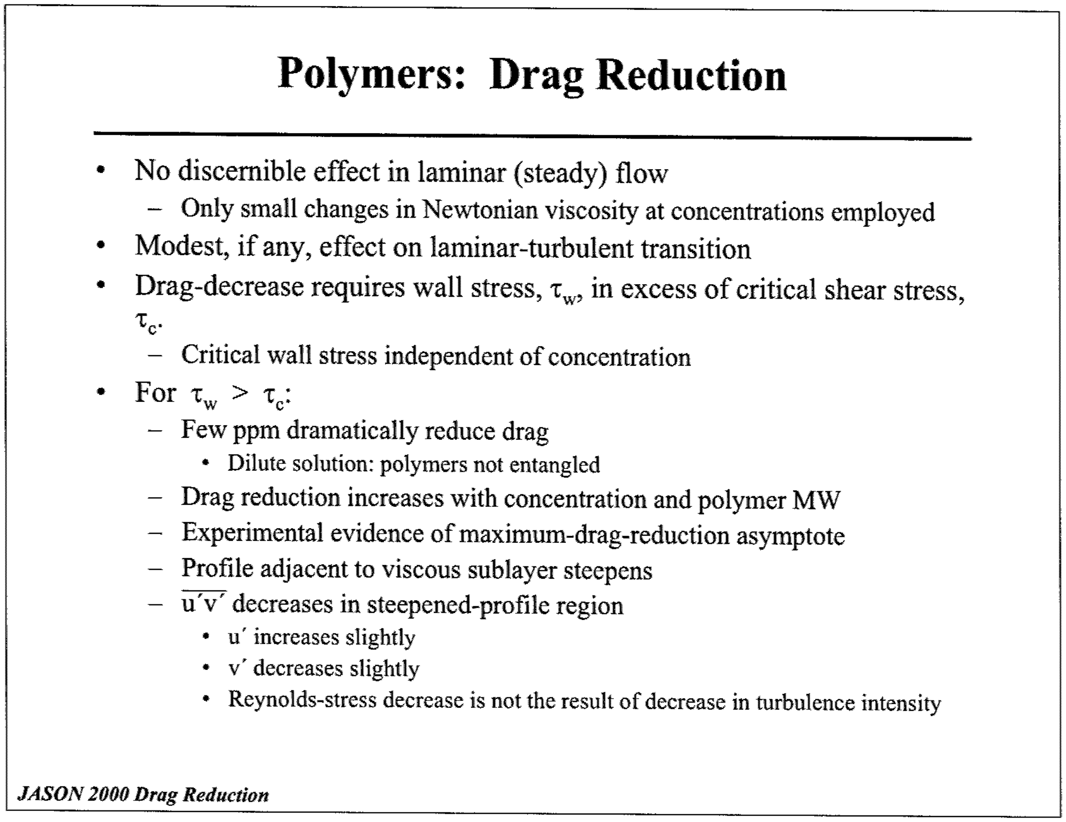
- Zimm (1956) frequency, ω_Z, provides the basic relaxation rate that must be met for the onset of polymer viscoelastic activity.
  - $\omega_Z \approx 10^5$ rad/s typical; $t_Z \sim 10^{-4}$ s ⇔ strain rates $\sim 10^8\ s^{-1}$ for FastShip BL

Polymer molecular weights can be high ($\approx 5\text{-}6\times10^6$ Daltons).

The convected-Jeffreys and Oldroyd-B (1950) models are discussed in Bird *et al.* (1987, vol. 1). Those models describe coupled convected elastic (tensor) stress fields.

Under the influence of thermal excitations (self-avoiding random walk), long articulated polymer chains coil so as to be circumscribed by quasi-spherical boundaries. The coiled-chain extent is measured by the (rms) *radius of gyration*, R_g. Such a coiled chain will deform, when subjected to hydrodynamic (viscous) forces in a strain-rate field, and stretch to an extent $R > R_g$. A free energy of deformation, F, can be associated with such elongations, in terms of an effective (Hookean) linear (entropic) spring constant, κ_H, as above.

The Zimm frequency, $\omega_Z = \kappa_H/\gamma_S$, is the scaling coefficient of the ratio of the left-hand side and the first term on the right-hand side of the equation in the frame. It is a function of the temperature, T, the fluid viscosity, μ, and the polymer-chain size, R_g, *i.e.*, a function of the *fluid* and the size of the crumpled *polymer chain*, but not a function of the *flow*.



Polymers: Drag Reduction

- No discernible effect in laminar (steady) flow
  - Only small changes in Newtonian viscosity at concentrations employed
- Modest, if any, effect on laminar-turbulent transition
- Drag-decrease requires wall stress, τ_w, in excess of critical shear stress, τ_c.
  - Critical wall stress independent of concentration
- For $\tau_w > \tau_c$:
  - Few ppm dramatically reduce drag
    - Dilute solution: polymers not entangled
  - Drag reduction increases with concentration and polymer MW
  - Experimental evidence of maximum-drag-reduction asymptote
  - Profile adjacent to viscous sublayer steepens
  - $\overline{u'v'}$ decreases in steepened-profile region
    - u' increases slightly
    - v' decreases slightly
    - Reynolds-stress decrease is not the result of decrease in turbulence intensity

JASON 2000 Drag Reduction

At the concentrations employed (a few wppm) the influence of polymers on the Newtonian viscosity of the fluid is small. The effective viscosity can be estimated from the Einstein (1906) equation (*cf.* Landau & Lifshitz **6**, 1959), or the empirical Mark-Houwink relation,

$$\lim_{c_p \to 0} \left(\frac{\mu - \mu_0}{c_p \, \mu_0} \right) \cong K_\mu \, M_w^{\,a_\mu}$$

In which K_μ and a_μ are empirical constants specific to the polymer-solvent combination, and M_w is the polymer molecular weight. Virk (1975) tabulates these coefficients for some of the commonly employed polymers, *e.g.*, for (polyethylene oxide) PEO-water and M_w in units of 10^6 Daltons, $K_\mu = 8.75 \times 10^{-3}$ and $a_\mu = 0.79$.

The review article by Virk (1975) can be consulted for experimental evidence of the lack of discernible influence on laminar-to-turbulent transition (Fig. 1), a critical wall shear-stress, τ_c, that is independent of *Re* (Fig. 2a), and polymer concentration (Fig. 2b). For PEO, Virk reports,

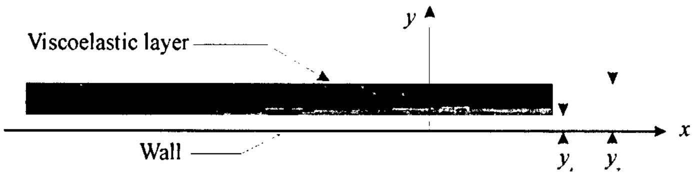
$$\left(\frac{R_g}{\text{nm}} \right)^3 \frac{\tau_c}{\text{N/m}^2} \approx 4.4 \times 10^6 \, .$$

Documentation for the drag-reduction attributes listed, for $\tau_w > \tau_c$, can also be found in the Virk (1975) review.

Polymers: Drag-Reduction Models — I

- Common element: Activation/extension rate ⇔ Zimm frequency

$$\underbrace{\frac{u(\lambda_d)}{\lambda_d} \approx \frac{U}{\delta} Re^{1/2}}_{\text{dissipation strain rate}} > \underbrace{\frac{u(\lambda)}{\lambda}}_{\text{inertial-eddy strain rate}} > \omega_Z\,, \quad \text{for } \lambda_d < \lambda < \delta$$



- In a boundary layer, this would be confined to a viscoelastic layer between,

$$y_d \approx \frac{\nu}{u_\tau} \ : \ \text{viscous/dissipation distance}$$

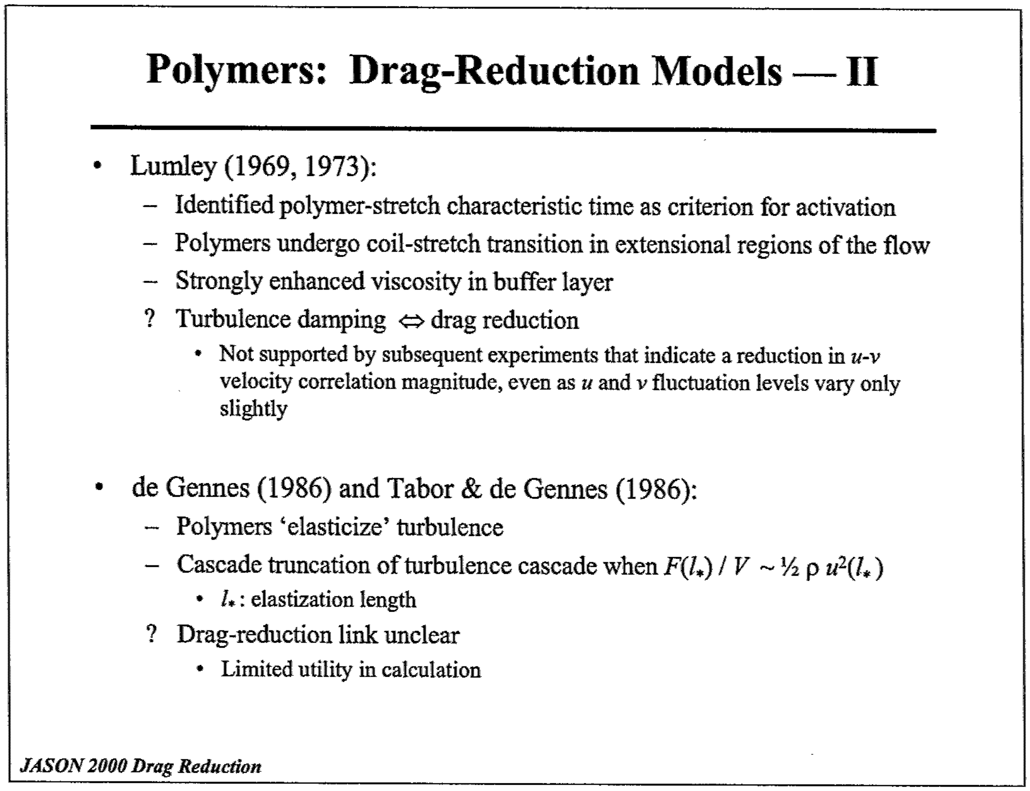
$$y_Z \approx \frac{u_\tau}{\omega_Z} \ : \ \text{distance from wall where Zimm frequency is exceeded}$$

Experimental evidence supports the notion that the critical shear stress is related to the characteristic *time* (Zimm frequency) for polymer activation, as conjectured by Lumley (1973). In the wall region, the characteristic length and time scales are, $\lambda_\nu = \nu / u_\tau$ and $t_\nu = \lambda_\nu / u_\tau$, respectively (*cf.* Slide 14).

Drag-reduction onset occurs at $R_g\, u_\tau / \nu \approx 8\times10^{-3}$, while the ratio of time scales is $t_Z\, u_\tau^2 / \nu \approx 2$, *i.e.*, the macromolecules are much smaller than the characteristic boundary-layer (viscous) length scales, but have a (Zimm) relaxation time (*cf.* Slide 19) that is comparable to the viscous time scale (Virk 1975).

The inequality range outlined in the frame derives from the assumption that Kolmogorov scaling can be used in the vicinity of the wall. In that expression, λ_d, the dissipation length scale, is assumed approximately equal to $\lambda_K \equiv (\nu^3/\varepsilon)^{1/4}$, the Kolmogorov length scale, where, here, ε is the kinetic-energy dissipation (per unit mass).

That polymers are not expected to act within the viscous sublayer, *i.e.*, for $y^+ < 5$, or so, was also postulated by Lumley (1969, 1973). The resulting viscoelastic layer, for $y_d < y < y_Z$, then defines a region within which the flow is not damped by viscosity ($Re > 1$) and where strain rates are high enough to activate the polymers, defining the extent where local momentum transport is modified (suppressed).



Polymers: Drag-Reduction Models — II

- Lumley (1969, 1973):
  - Identified polymer-stretch characteristic time as criterion for activation
  - Polymers undergo coil-stretch transition in extensional regions of the flow
  - Strongly enhanced viscosity in buffer layer
  - ? Turbulence damping ⇔ drag reduction
    - Not supported by subsequent experiments that indicate a reduction in u-v velocity correlation magnitude, even as u and v fluctuation levels vary only slightly
- de Gennes (1986) and Tabor & de Gennes (1986):
  - Polymers 'elasticize' turbulence
  - Cascade truncation of turbulence cascade when $F(l_*) / V \sim \frac{1}{2} \rho u^2(l_*)$
    - l_* : elastization length
  - ? Drag-reduction link unclear
    - Limited utility in calculation

Lumley correctly theorized that polymers act beyond the viscous sublayer and that drag-reduction onset is associated with a match between viscous and Zimm relaxation time scales (Slide 21). He further conjectured that the net effect was equivalent to an increase in effective viscosity and a kinetic energy damping, with an attendant reduction in velocity fluctuations and near-wall Reynolds stress. The latter conjecture is not borne out by experiment (*e.g.*, Virk 1975).

Related models are reviewed by Toonder and Nieuwstadt (1999), who also discuss an idea by Joseph *et al.* (1986) and Joseph (1990), who argued for viscoelastic behavior and "shear waves", and conducted some experiments to look for them. Toonder and Nieuwstadt conclude that this idea "… is only vaguely formulated and has not been experimentally tested or theoretically elaborated."

A different conceptual framework was put forth by de Gennes (1986) and Tabor & de Gennes (1986), who based their proposal of polymer-flow interaction on polymer deformation. To calculate the degree of extension, they invoke Kolmogorov scaling to associate a unique strain rate to eddy size. They hypothesized that the turbulent cascade is "truncated" at scales smaller that than l_* required for polymer activation (see frame), at equipartition of eddy potential (elastic) and kinetic energy. Interestingly (though not discussed by de Gennes), such an equipartition implies a competition between Reynolds and elastic stresses, with a concomitant quenching of turbulence production and momentum transport.

Polymers: Elastodynamic Equations — I

- P. Diamond *et al.* (1992) JSR-89-720.
  - Elastic-stress tensor: $Q_{ij}(\mathbf{x},t) = \int d^3\mathbf{q}\; q_i\, q_j\, f(\mathbf{q},\mathbf{x},t)$
  - with evolution/transport equations:

$$\frac{\mathrm{D}Q_{ij}}{\mathrm{D}t} = \underbrace{Q_{ik}\frac{\partial}{\partial x_k}u_j + Q_{jk}\frac{\partial}{\partial x_k}u_i}_{\text{stretching}} - \underbrace{4\omega_Z Q_{ij}}_{\text{Zimm relaxation}} + \underbrace{D_p\nabla^2 Q_{ij}}_{\text{diffusion}} + \underbrace{\frac{4k_B T}{\gamma_S}\delta_{ij}}_{\text{thermal support}}$$

$$\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\mathbf{u} + \nabla\cdot\underbrace{(c_p\kappa_H\mathbf{Q})}_{\text{viscoelastic stress}}$$

$$\frac{\mathrm{D}c_p}{\mathrm{D}t} = D_p\nabla^2 c_p$$

- Restricted to Hookean springs (linear response)
- Analogous to MHD — exception: Zimm relaxation!

Polymers: Elastodynamic Equations — II

- Elastization ⇔ drag reduction (Diamond, Medvedev, Nelson, Gruzinov: in preparation)
  - Equations do not predict discernible effect for laminar pipe flow
  - Equations predict elastodynamic waves (akin to Alfvén waves)
  - Elastization
    - conversion of turbulence kinetic energy to elastic-wave energy
    - elastic/kinetic energy equipartition (as in MHD)

  → Elastic-tensor stress can oppose Reynolds stress

    → $\tau_{\mathrm{eff}} \approx -\overline{\rho u' v'} + c_{\mathrm{p}}\, \kappa_{\mathrm{H}}\, Q_{xy}$
    - Decreased momentum transport for $y < y_Z$
  - Pro's:
    - Framework for implementing de Genne's intuition on elastization
    - Recovers momentum-flux reduction w/o enhanced damping
    - Reveals dependence on polymer-concentration, c_{p}
  - Con's:
    - Restricted to Hookean (linear) springs
    - Has not confronted boundary-layer structure/dynamics (horseshoe vortices, *etc.*)

Polymers: Pro's

- Small amounts needed (10-50 ppm) for large effects
- Proven drag-reduction capability
  - Polymers increased peak trans-Alaska pipeline capacity by 32,000 m^3/day, at 10 ppm levels
    - injected downstream of pumping stations to avoid degradation
    - No loss in effectiveness after 100's of km
    - Reduced heat transfer (maintain oil viscosity)
  - Used in storm sewers to increase peak capacity

* Unaffected by sea state in full-scale (20-36%) drag-reduction trials (Highburton 1968).

* 47% drag reduction measured at 64 knots (Tuna 1971-1974).

* Higher drag reduction for rough walls

* Compatible with sea water

JASON 2000 Drag Reduction

Polymer drag-reduction figures on the trans-Alaska pipeline system and on storm sewers are from Hoyt (1990).

Drag-reduction data cited for the Highburton (1968) and Tuna (1971-74) tests are from the Ryan (2000) briefing. The latter was a buoyant, torpedo-like vessel, with 25 m^2 surface area and is significant in that it approaches the Reynolds number and strain-rate regime of interest in the Fast-Ship context.

That higher drag reduction is observed for rough walls was noted by Debrule and Sabersky (1974) in their pipe-flow experiments. This appears to be corroborated by experiments in progress at this time at PSU/ARL (Ryan 2000, pvte. comm.).

Polymers: Con's

- Some logistical complexity
- Unknown, as yet, drag-reduction etiology
  - Extrapolation to high *Re*'s uncertain
  - Little guidance for optimization
- Rapid mixing
  - Higher required injection rates
  - Inhomogeneous influence along streamwise extent
- Polymers break (degrade) at high strain rates (speed)
  - When local strain rate exceeds polymer tensile strength
  - Stronger polymers can be made
    - likely to degrade more slowly
- Injection noise

Surfactants — I

- Drag-reduction benefits recognized by Mysels *et al.* (1949 patent, +)
- Maximum drag-reduction asymptote higher (better) than for polymers (Zakin *et al.* 1996)
- Dilute solutions (not entangled) at concentrations where effective drag-reducers
  - ≈ ×10 wppm high-MW-polymer concentrations
  - ➤ Decrease surface tension: relevant to microbubble-size control
- Complex molecules with hydro-philic/-phobic ends self-assemble (reversibly) to form:
  - micelles,
  - layered structures,
  - vesicles, and
  - worm-like chains

Depending on surfactant geometry, environment salinity, etc.

- If surfactant assembly is broken by turbulence (high strain-rate region), structure self-heals, in regions of lower strain-rate
  - Used in closed-loop heating systems to reduce pumping costs

Surfactants — II

- Worm-like chains:
  - have a probability distribution of contour (chain) lengths, L,

$$\Pr(L) \propto e^{-L/L_0}\ ; \quad L_0 = d_s\,\varphi^{1/2}\,e^{E_c/(2k_BT)}$$

where,

- $d_s \sim 4$ nm is the surfactant-worm diameter
- $\phi \sim 10^{-4}$ surfactant-chain volume fraction
- $E_c \sim 0.37$-0.40 eV (~ 15-20 k_BT, at room-T) scission (tearing) energy

  - Persistence length: $l_p \approx 16$ nm
  - Radius of gyration:

$$R_g \approx \sqrt{l_p\,L_0} \approx (8\,\mathrm{nm})\,\varphi^{1/4}\,e^{E_c/(4k_BT)}$$

  - Number-density of surfactant polymers:

$$c_p \approx \left(2.5\times10^{20}\,\mathrm{cm}^{-3}\right)\varphi^{1/2}\,e^{-E_c/(2k_BT)}$$

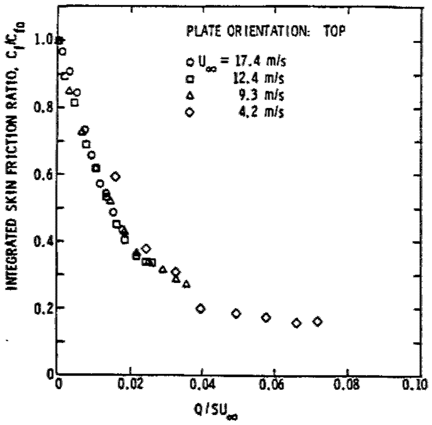
  - Non-Newtonian (viscoelastic) stress contribution (as for high-MW polymers):
    - $\boldsymbol{\tau}^{(\mathrm{pol})} = c_p\,\kappa_H\,\mathbf{Q}$, with $\kappa_H = k_BT / R_g^2$ the Hookean spring constant

JASON 2000 Drag Reduction

Polymer-Surfactant Comparison

	PEO (polymer)	C_{14}TABr (surfactant)
Drag reduction	~ 4-fold	~ 3-fold
Persistence length: l_p	~ 1.5 nm	~ 16 nm
Contour (chain) length: L	~ 10^4 nm	~ 350 nm
Segments: $N = L / l_p$	~ 6500	~ 20-25
Radius of gyration: R_g	~ 300 nm	~ 75 nm
Polymer concentration: C_p	~ 10^{14} cm^{-3}	~ 3×10^{14} cm^{-3}

Microbubbles



Merkle & Deusch 1990

- Microbubble injection results in comparable drag reductions (McCormick and Bhattacharya 1973)
  - $[\Delta C_f / C_f]_{\max} = 60 - 80\%$
  - Similarities in phenomenology to polymers/surfactants.
  - However:
    - Comparable gas-volume fractions (~80%) found to be required for reduction at such levels
    - A consequent reduction in the local two-phase fluid density, ρ, implies a comparable reduction in local Reynolds stress: $-\rho u'v'$
- High pumping costs
  - Comparable (on paper) with anticipated drag-reduction benefits

JASON 2000 Drag Reduction

Microbubble Dynamics — I

- Microbubble size distribution adjusts to local flow:
  - Breakup: Balance between capilarity and shear-stress/pressure forces (Hinze 1955)
  - Coalescence: When film between adjacent bubles drains to critical thickness, h, and ruptures (Thomas 1981)

$$0.7\,(\sigma/\rho)^{3/5}\,\varepsilon^{-2/5} \sim \tau_w^{-3/5} \;<\; d_b \;<\; 2.4\,(\sigma^2 h/\mu\rho)^{3/5}\,\varepsilon^{-1/4} \sim \tau_w^{-3/8}$$

with σ the surface tension and $\varepsilon \sim u_\tau^3 / \delta_2$ the BL kinetic-energy dissipation rate

- Microbubbles, at void-fractions of interest (comparable to % drag reduction), substantially lower sound speed
  - Compressibility/turbulence-damping effects
  - Conversion of TKE to acoustic radiation; significant modification of BL acoustics
  - "Supersonic" boundary layer

Microbubble Dynamics — II

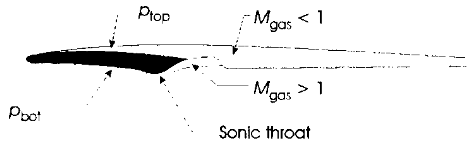
- Microbubbles can impart elastization to the flow with phenomena that parallel polymer/surfactant rheological consequences and dynamics
  - Smaller bubbles more effective
    - ρ-reduction from void fraction not the whole story
    - Reduction in required volume fraction
  - Wall spectral data from pressure and hot films show loss of high-*f* fluctuations

$$d_b > \lambda_K \;\Rightarrow\; (\sigma / \rho\, \varepsilon^4)^{3/5} / \nu^{3/4} > 1 \qquad \text{Harder as } U \uparrow$$

  - Polymers and microbubbles both reduce turbulence statistics skewness
    - Decrease of high-amplitude events
- Electrolytic microbubble generation?
  - First by McCormick and Bhattacharya (1973)
  - Generate bubbles at/near wall, where needed
    - Microbubbles generated within $y^+ < 10$.
  - Gas volume flow rate estimated to be much lower (10^{-4} – 10^{-5}) than for porous-wall injection
  - Pulsed/adaptive?
  - Attractive, but net power gain may be difficult:
    - Low seawater electrical conductivity, σ_e.

Air Films

- Air films isolate high-∇u near-wall region from water.
  - Reduced $\tau_w = [\mu(\partial u/\partial y)]_w$, since $\mu_{air} \approx \mu_{water} / 80$
- Can be more effective than polymers/microbubbles:
  - If stable
    - at high *Re*'s
    - Rayleigh-Taylor instability
    - Interfacial waves
    - Freestream turbulence
  - If pumping costs can be recovered
  - JSR-99-215 proposal
    - Exploit high-pressure ratio at TE to drive supersonic flow out of convergent-divergent nozzle



- Graceful "failure"
  - Air film converted to microbubble layer

E&M Turbulence Control (EMTC) — I

- Exploit conductivity of sea water
- Lorenz force:
  - Permanent/electro-magnets in wall
  - $\mathbf{f} = \mathbf{j}_e \times \mathbf{B} \approx \sigma_e \mathbf{E} \times \mathbf{B}$ may be streamwise, spanwise, or wall-normal
  - Wall electrodes can drive currents $\perp \mathbf{B}$
- Does it work?
  - Sometimes drag increase, sometimes drag decrease
    - Cannot predict which
    - Empirical — no theory for turbulent flow
    - Depends on (many) specific parameters
  - Both stationary and travelling-wave E&M fields
    - Experiments (Brown): up to ~15% reduction reported
    - Simulations (Kim & Karniadakis): up to ~35% reported (low-/moderate-Re)
  - Unknown scaling with *Re*

E&M Turbulence Control (EMTC) — II

- Efficiency: $\eta_{\mathrm{EM}} = \frac{P_{\mathrm{DR}}}{P_{\mathrm{EM}}} \sim \frac{\sigma_e B^2 \delta}{\rho u_\tau}$
  - |**B**| limited to ~ 0.5 T (5 kgauss)
  - Low conductivity of seawater (σ_e ~ 4.3 mhos/m — PC: Siemens/m)
    $\Rightarrow$ Large E $\Rightarrow$ large resistive loss
  - CFD (Kim, Karniadakis) indicates $\eta_{\mathrm{EM}} \approx 10^{-3}$.
- Can it be improved to be useful?
  - Closed-loop control: apply force only where/when useful
  - Adaptive/learning (neural-net) algorithm?
  - CFD indicates improved efficiency to $\eta_{\mathrm{EM}} \sim 1/6$ (Kim)
  - Unknown limits and whether $\eta_{\mathrm{EM}} > 1$ is possible.
- Practical issues
  - Skin covered with electromagnets/electrodes
    - $10^8 - 10^{10}$ electrodes for full-scale vessel
  - Low voltage $\Rightarrow$ high-current supply

Active-Feedback Control

- Pro's:
  - Effectiveness demonstrated (simulation) in low-*Re* turbulent boundary flows
  - Potential with emerging MEMs technology

- Con's:
  - Actuation and efficacy unknown at high *Re*'s
  - Effective, realizable, survivable actuation as yet undefined
  - Unknown efficiency (Power saved *vs*. expended)

Conclusions

- Required *FastShip* ×3-4 drag-reduction levels appear to be within reach.
- However, real requirement (*net* power reduction, for given U) is harder:

$$\underbrace{C_D}_{\text{Reduced } C_D} + \underbrace{\frac{P_{\mathrm{DR}}}{\rho U^3 A/2}}_{\text{Normalized drag-reduction power-cost}} < f_{\mathrm{DR}} \underbrace{C_D^{(0)}}_{\text{“Natural” } C_D}, \quad \text{with} \quad f_{\mathrm{DR}} \le 0.25 - 0.30$$

- P_{DR} is the power, from the primary power plant, to effect drag-reduction (in the case of EMTC, possibly with its own efficiency penalties)
- Care required in designing/interpreting experiments/simulations to account for proper (total) shear stress at the wall (drag) and P_{DR}, drag-reduction power-expended
  - Generalized von Kármán momentum integral
  - $\mu\,(\partial u/\partial y)_{y=0}$ may not include necessary contributions from viscoelastic stresses for polymers/surfactants, or Lorenz forces (in case of EMTC)
- Proposed unified theoretical framework to account for behavior of
  - high-MW polymers and
  - Surfactants
- High community interest: 35,108 “drag-reduction” hits on Netscape

Recommendations — I

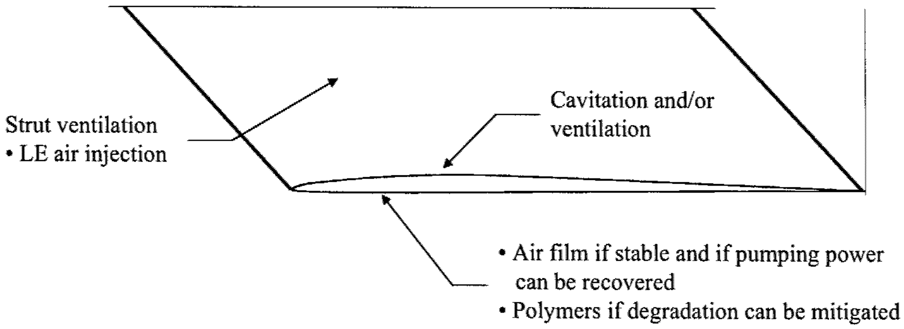
- * Solve turbulence problem
  - Was not accomplished this July
- Polymers:
  - Proposed elastodynamic equations
    - Boundary conditions? Steady-flow response?
    - Linear-stability analysis to verify/validate onset phenomena
    - Computer simulations (DNS) to investigate implied drag-reduction mechanisms
    - Validation experiments (e.g., pipe flow) of predicted Alfvén-like waves
      - Dispersion relation: $\omega(\mathbf{k}) = -2i\omega_Z \pm [(c_p k_H Q_0 / \rho) \; k^2 - 4\omega_Z^2]^{1/2}$
      - Influence on turbulence: $k > k_{act} = 2\omega_Z \; / (c_p k_H Q_0 k^2 / \rho)^{1/2}$ attenuated.
    - Experimental investigation of modifications to bursting events and near-wall flow structure
  - Extend elastodynamic framework
    - Lift limitation of linear response (infinite extensibility)
      - Linear response does not capture measured non-Newtonian (shear-rate-dependent) shear viscosity
      - Undertake hybrid (continuum/particle) simulation of non-linear elastodynamic "dumbell-fluid"
      - Contribution of polymer stiffening at large extensions (prior to breaking)
      - Likely to be important in impeding high-strain-rate events (hair-pin vortices)
  - "Designer polymers": Prescribed stress-strain relation?

Recommendations — II

- Surfactants
  - Exploit self-assembly/-healing to tailor non-Newtonian behavior where needed
    - Flow-adaptive response
  - Use in closed-loop heat-exchange systems to reduce power/noise
- Microbubbles
  - Explore flow-elastization idea
  - Develop unified theoretical framework for
    - polymers
    - surfactants
    - microbubbles
- Vapor cavities and air films
  - Stability issues at high *Re*'s
  - Extend present computational capabilities to accommodate dynamic-pressure variations in cavitating/ventilated regions
  - Study air-film injection-power-recovery technologies
  - Air-film → microbubble transition

Recommendations — III

- If hydrofoil based, Fast-Ship DR technology likely to be composite:
  - Optimized to different flow/pressure regimes



Strut ventilation
- LE air injection

Cavitation and/or ventilation

- Air film if stable and if pumping power can be recovered
- Polymers if degradation can be mitigated

  - Revisit system optimization, applying potential DR benefits to various parts to explore changes in shape, structure, and consequent system *L /D*.

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