On Swell of viscoelastic fluids

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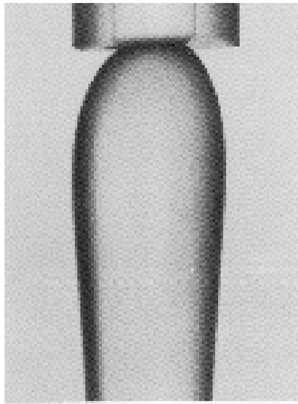
Outline

- What is die swell ?
- What does delayed die swell mean ?
- The important parameters.
- Numerical simulations, deeper view of the phenomena.
- Understanding through most recent results.

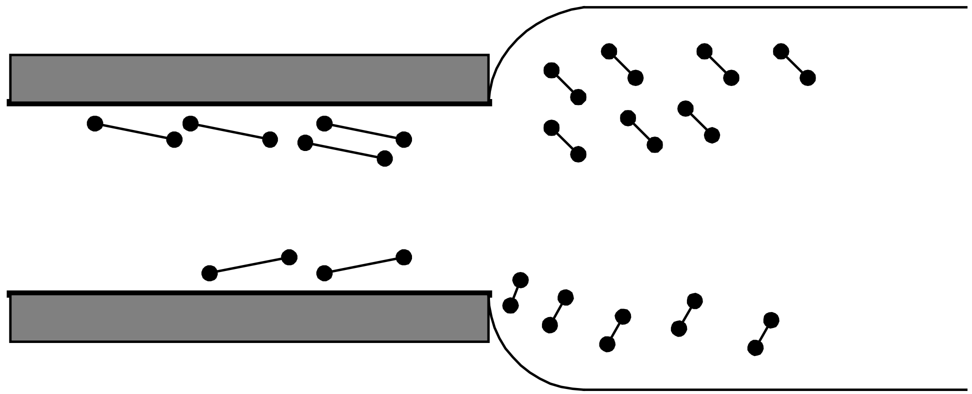
Where can we notice die swell effects ?

- Extrusion of polymers (molten plastics)
- For any viscoelastic extruded solution (Cloitre, 1998), no change of structure !



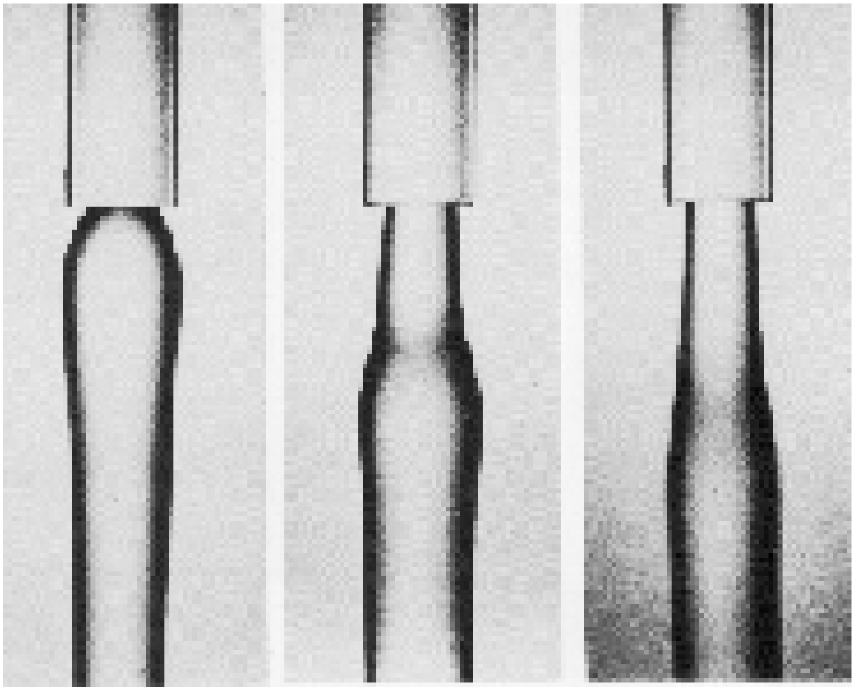
Description of die swell

- Swell of the jet
- Lower rate of extrusion
- Effect of elasticity when the shear stops: N1 is high, elastic recovery



What is delayed die swell ?

- Observed by increasing the extrusion velocity



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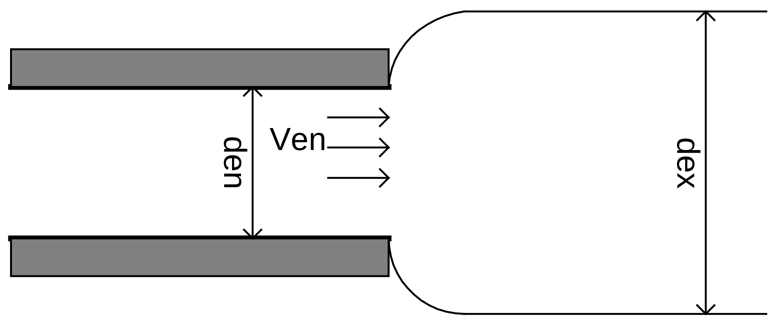
Important parameters

- Weissenberg number : $We = \frac{\lambda V_{en}}{d_{en}}$
- Reynolds number : $\mathrm{Re} = \frac{\rho V_{en} d_{en}}{\eta}$
- Viscoelastic Mach number: $M = \frac{V_{en}}{c} = \sqrt{\mathrm{Re} \cdot We}$
- Elasticity number: $E = \frac{\lambda \eta}{\rho d_{en}^2} = We / \mathrm{Re}$



Speed of shear waves into a fluid at rest

$$\text{Maxwell model}: \sigma_{\mathrm{ij}} + \lambda \sigma_{ij,t} = \eta d_{ij}$$

$$\text{Momentum equation}: \rho \cdot \mathrm{u}_{\mathrm{i,t}} = \sigma_{\mathrm{ij,j}}$$

$$\text{Pure shear}: \mathrm{u} = \mathrm{u(y,t)}$$

Lead to:

$$\lambda \rho \cdot u_{tt} - \eta \cdot u_{yy} + \rho \cdot u_t = 0$$

$$\text{so } \mathrm{c} = \sqrt{\frac{\eta}{\lambda \rho}}$$

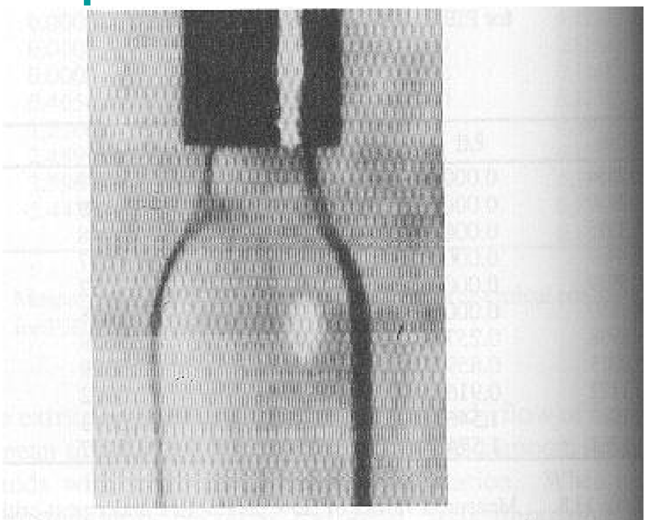
Delayed die swell

Experiments by Joseph, Matta & Chen (1987)

- General phenomenon
- Critical phenomenon
- Steady or unsteady (large relaxation times λ)
- Less apparent: low λ, low η

Critical conditions

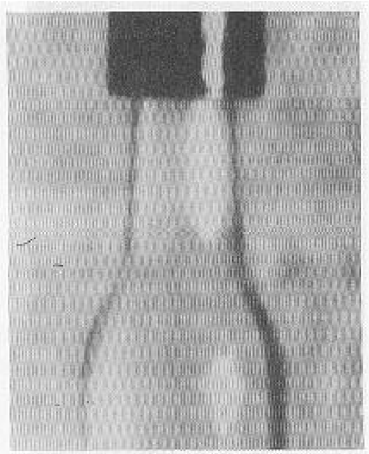
- U_C, D/d, L/d decrease with pipe diameter
- Critical Mach number M_C >1 at exit
- After the swell M_L<1
- Inflection point



. Extrusion of PIB/D, 6% under post-critical conditions: $[d,\bar{u}(0)/c,M(L)] = [3.175\ mm, 1.02, 0.247]$.

Post critical conditions

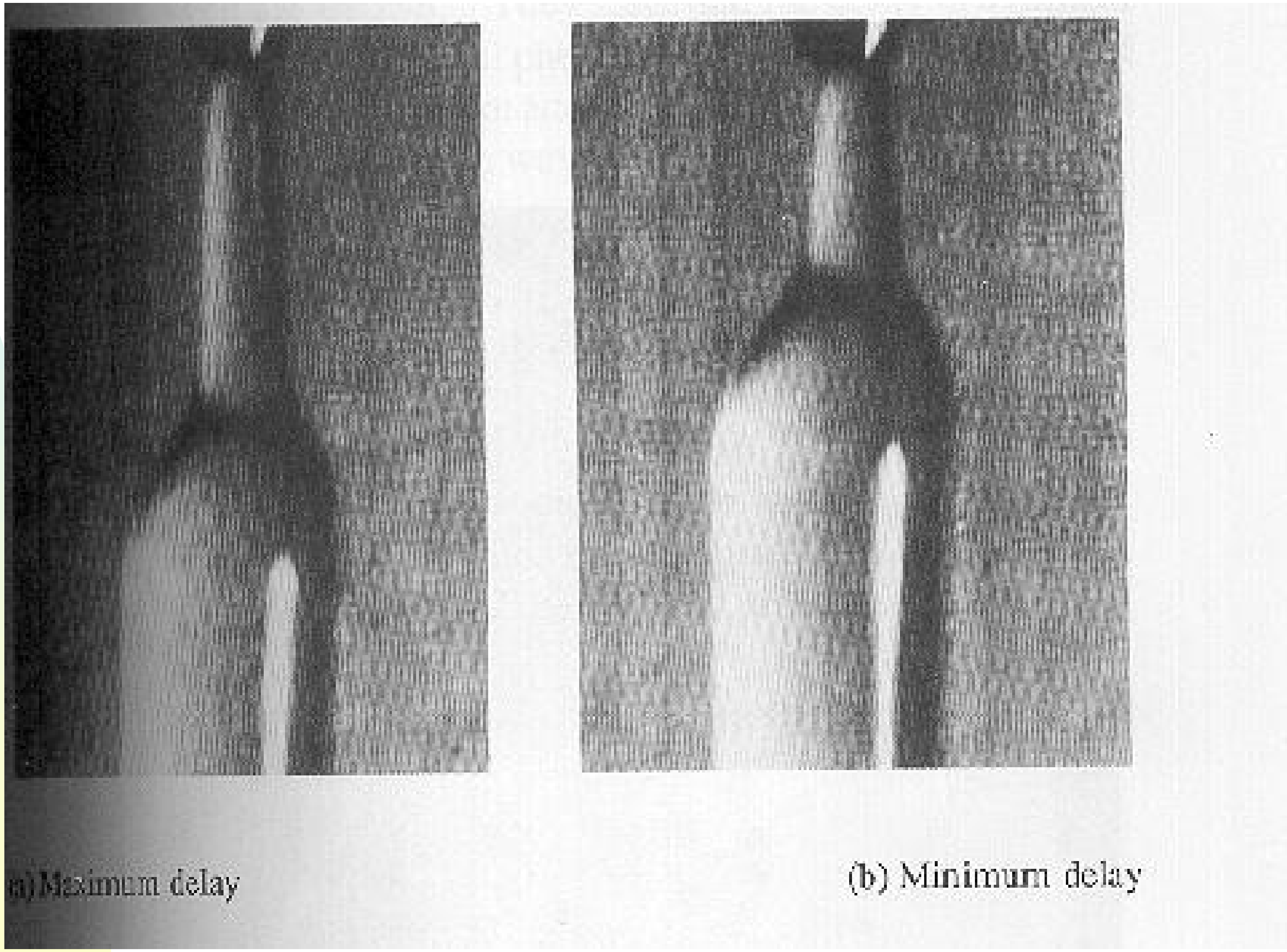
- *L* increases with u
- D/d increases and then decreases
- M_L increases with u (less than 1)
- M_L, D/d, (L-*L*)/d decrease with d, strength of shock is greater for small d



. Extrusion of PIB/D, 6% under post-critical conditions: [d,ū(0)/c,M(L)] =[3.175 mm,1.28,0.327].

High rates of extrusion

- Unsteady flows for large time of relaxation



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High rates of extrusion

- Smoothing

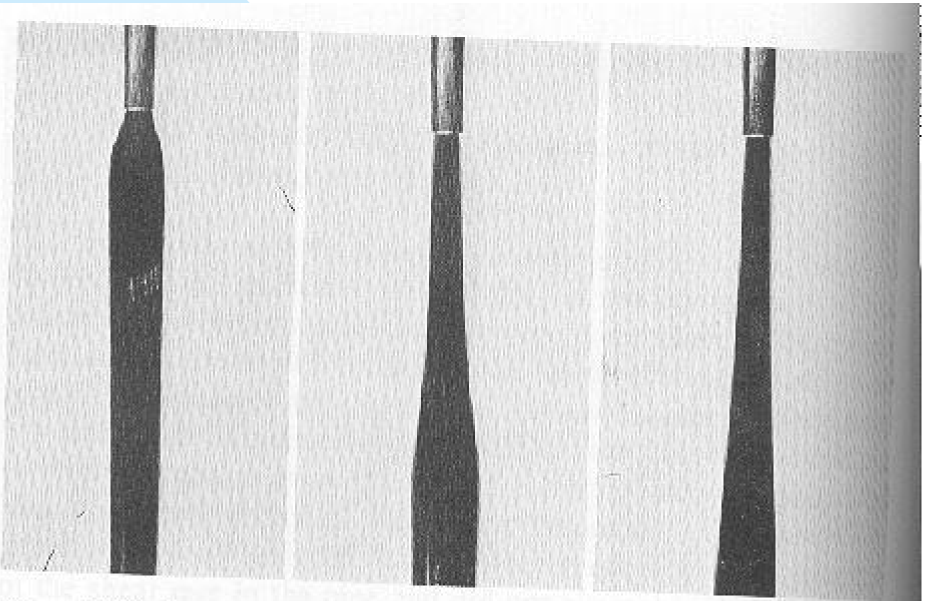
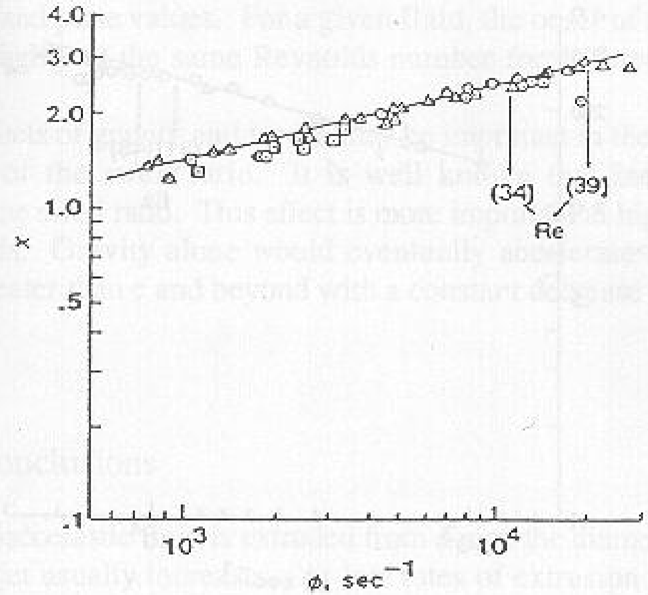


Figure 13.18 Steady response of K-125, 5% under post-critical conditions: [d,c] = [2.38 mm, 45.5 cm/s]. [Q(cm^3/s), ϕ(1/s), $\bar{u}(0)/c$, D/d, M(L)] = (a) [8.13, 5780, 3.8, 2.3, 0.72], (b) [21.5, 15360, 10, 2.6, 1.5], (c) [23.8, 16930, 11.1, 2.41, 1.92]. The response of K-125, 5% is similar to Elvacite, 9.8%. The swell profile is "smooth" when M(L)>1.



re 13.19 Swell ratio χ=D/d as a function of the apparent rate of shear $\phi=8\bar{u}(0)/d$ for Elvacite/9.8% at T=24±1°C, ○=2.39 mm, △=1.76 mm, and ⊡=1.25 mm. Figures 13.17(a), (b), and (c) correspond, respectively, to d=2.39 mm, ϕ=4418, ϕ=14823, and ϕ=17194.

Effect of gravity

- Control of jet shape

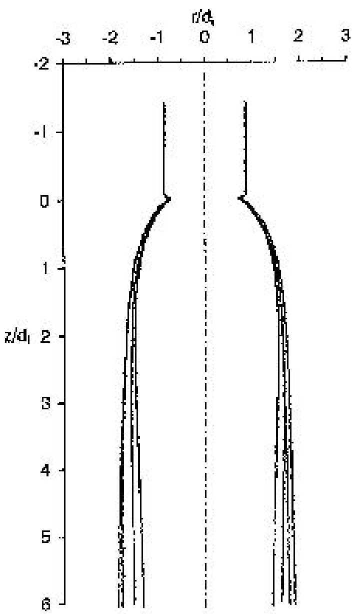


Fig. 5. Shapes of jets when the difference of density between the micellar solution and the external bath is concentration of the bath in sodium chloride and the corresponding density difference are, from the axis of sym outside: $C=0$ mol/l and $\Delta\rho=1.3\times10^{-2}$, $C=0.3$ mol/l and $\Delta\rho=7.5\times10^{-3}$, $C=0.45$ mol/l and $\Delta\rho=2.1\times10^{-3}$, and $\Delta\rho=1.2\times10^{-3}$. The density differences have been measured with an accuracy better than 10%.

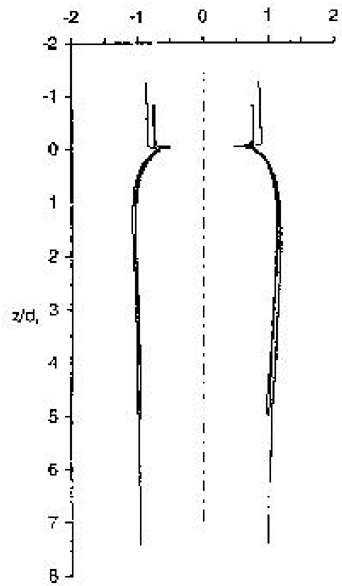


Fig. 6. Jets obtained for different needles and different flow rates are identical provided that the shear rates before exit are equal. Note that the coordinates r and z have been rescaled by the inner diameter of the needle. The shear rate in the needle is 248 s^{-1}; the experimental conditions are : $d_i=0.84$ mm and $Q=60$ ml/h, $d_i=0.60$ mm and $Q=22$ ml/h, $d_i=0.41$ mm and $Q=7$ ml/h.

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Sketch of delayed die swell

M. Cloitre et al. / J. Non-Newtonian Fluid Mech. 79 (1998) 157–171

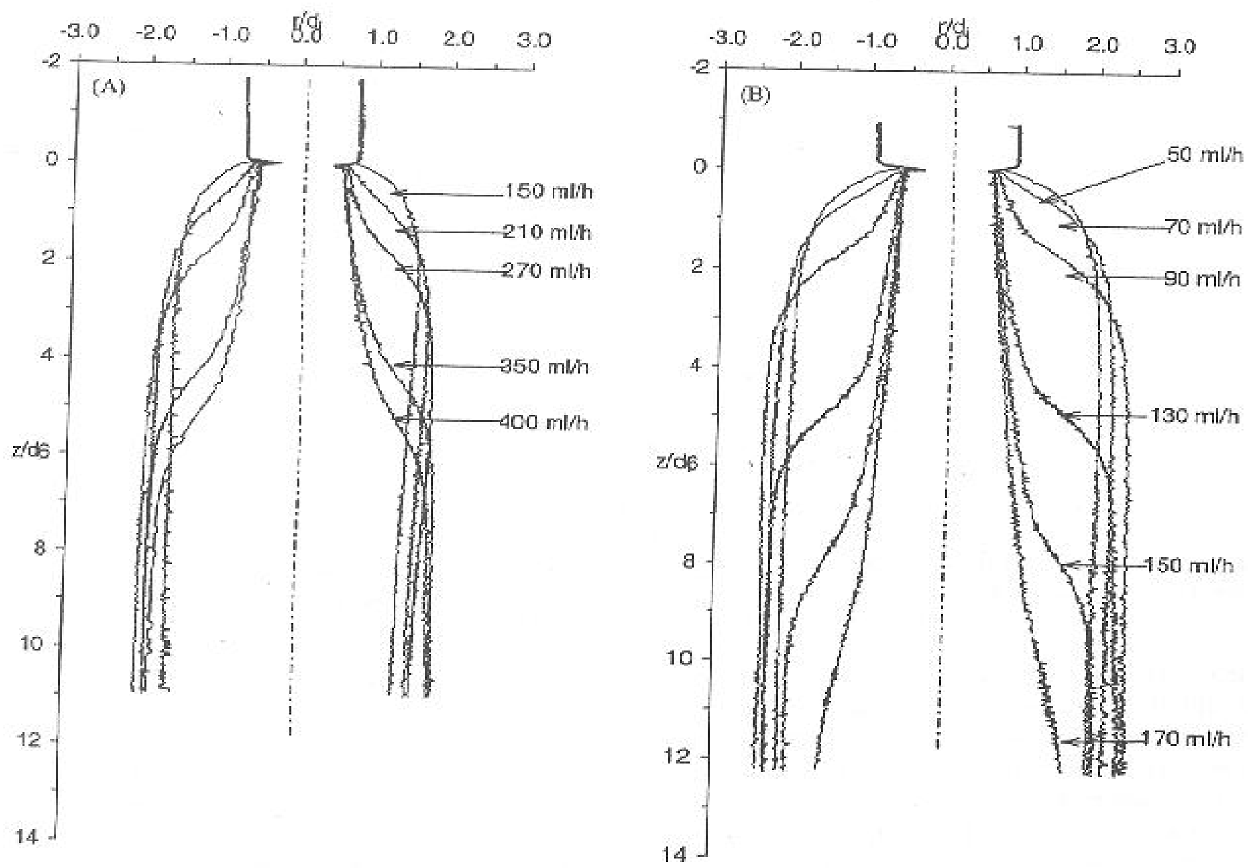


Fig. 7. Delayed-die swell in micellar solutions; the weight fraction of surfactants is 0.005; the diameter of the needle is d_i=0.31 mm in (a) and d_i=0.60 mm in (b). The measured values of flow rates, Reynolds numbers and Mach numbers are given in Table 2. The elasticity numbers are, respectively, E=0.5 (a) and E=0.1 (b).

Numerical methods for simulations
(Delvaux and Crochet, 1990)

- Upper convected Maxwell fluid + small viscous component to make the numerical solution easier: Oldroy B fluid.
- Calculations done with low values of E (stability !) ie no experimental validation !

Numerical methods for simulations
(Delvaux and Crochet, 1990)

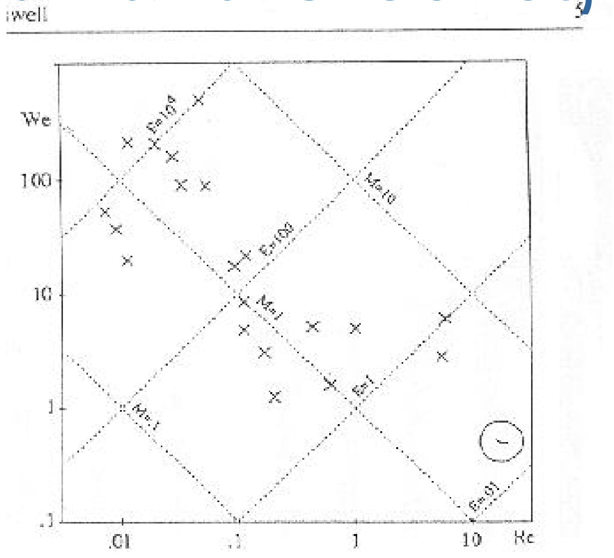
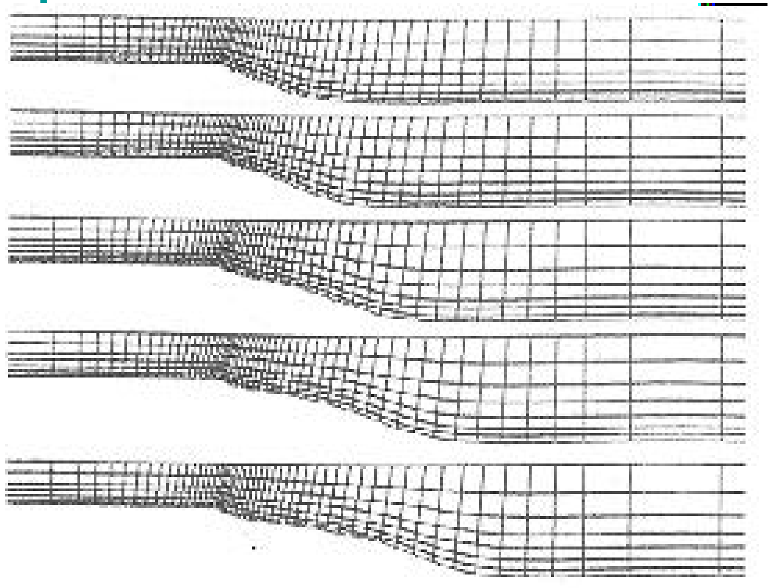


Fig. 5. Critical parameters for experimental results (×) [1] and numerical results (in the circle)

- Investigate the change of type which is related to : $T^* = \sigma + \frac{\eta}{\lambda} I - \rho \cdot \mathrm{vv}$
  T* definite positive = elliptic

Meshes used

- Important to avoid artificial (numeric) viscosity:
- Swell deform the fluid elements: inclined ray to preserve a better shape of the elements.



Results : Influence of the retardation time

- Swelling ratio decrease with λ
- Shape of the free surface is insensitive: no effects in delay !

Delvaux and Crochet, Numerical simulation of delayed die s

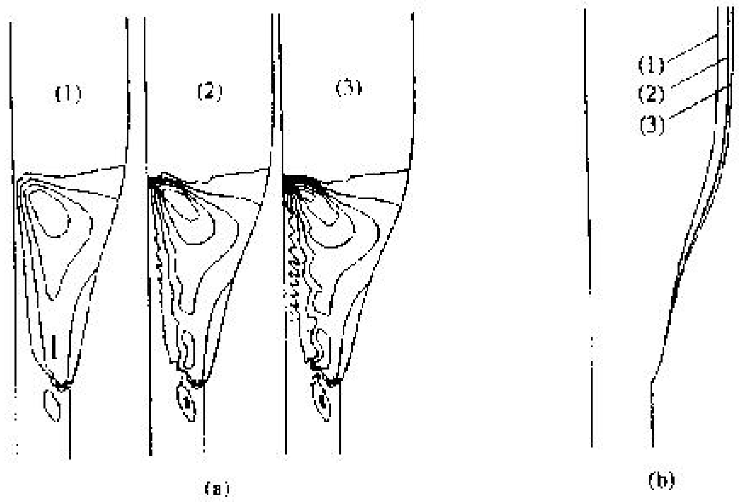


Fig. 12. Retardation time (λ^*) sensitivity analysis for case $M = 4.1$ and $E = 0.03$; (1) $\lambda^*/\lambda = 0.05$, (2) $\lambda^*/\lambda = 0.01$, and (3) $\lambda^*/\lambda = 0.001$: a) Contour lines of the radial velocity component u/V_{en}, with equal step = 0.4; b) Free surface shapes

Results : Influence of inertia

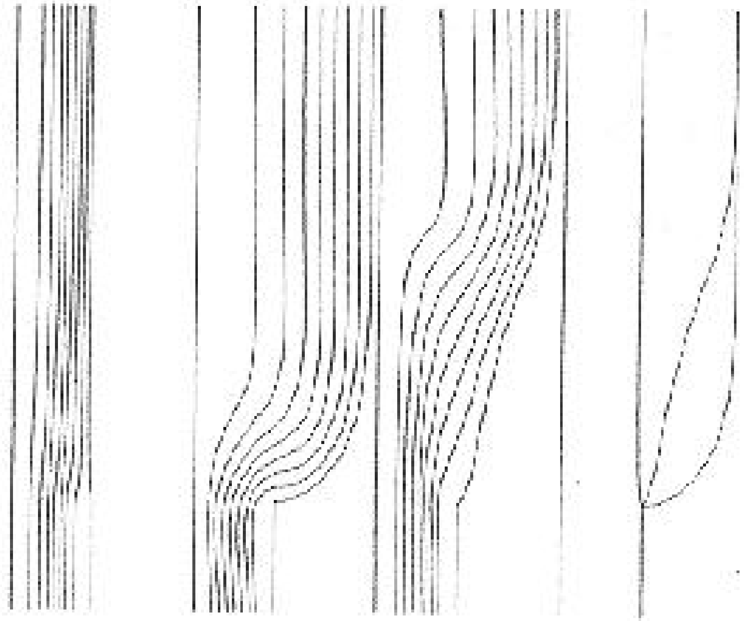


Fig. 7. Comparison between inelastic flow, viscoelastic flow without inertia, and inertial viscoelastic flow; (a) to (c), streamlines: the values are the same as in Fig. 6b; a) Inelastic ($We = 0$) flow at $Re = 24.1$; b) Viscoelastic flow at $We = 0.7$ without inertia ($Re = 0$); c) Inertial viscoelastic flow at $We = 0.7$ and $Re = 24.1$ ($M = 4.1$, $E = 0.03$); d) Superposed free surface shapes in the three cases, a) – c)

Results : Influence of elasticity

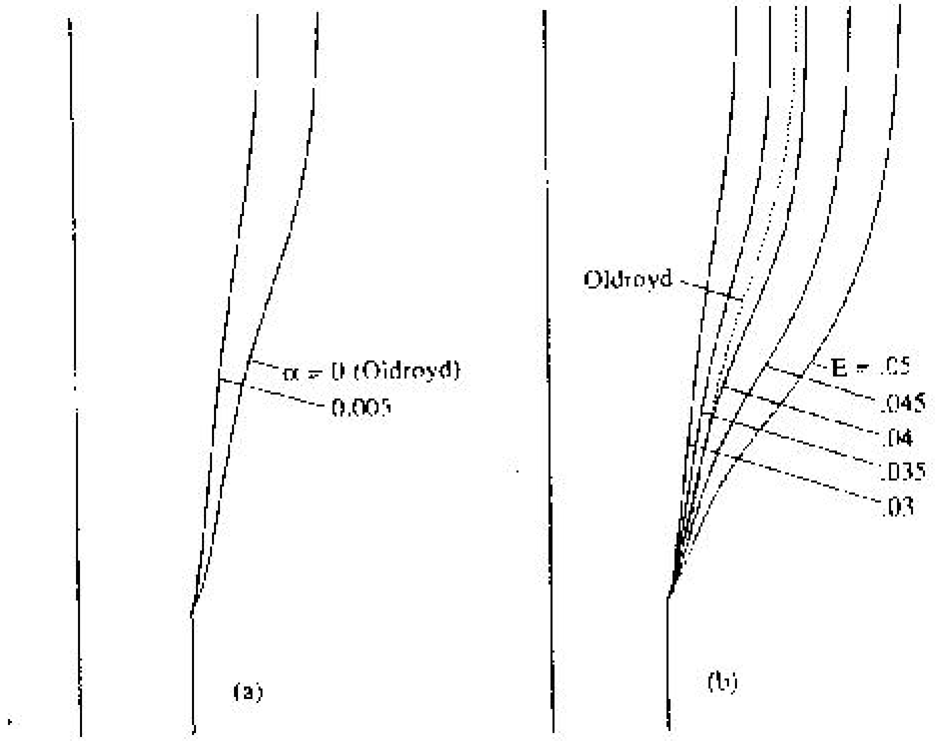
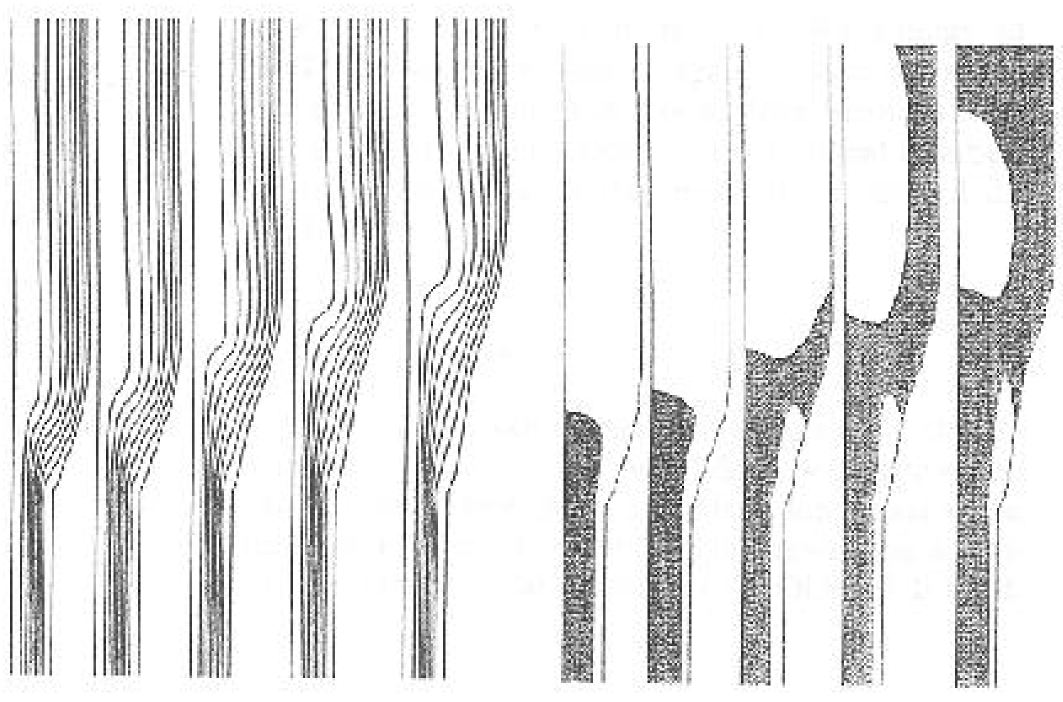


Fig. 13. Free surface shapes for a Giesekus fluid: a) Case ($M = 4.1$, $E = 0.03$); Giesekus parameter $\alpha = 0$ and 0.005; b) Case ($M = 4.1$, $\alpha = 0.005$); E ranging from 0.03 to 0.05

Results : Supercritical regions - vorticity contour lines

- Oldroyd B, E=0,03, M =2,3 to 5,9



(b) (c)

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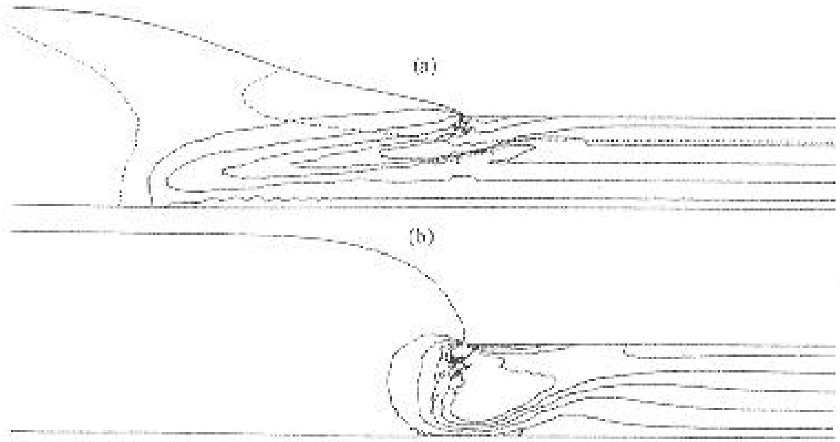


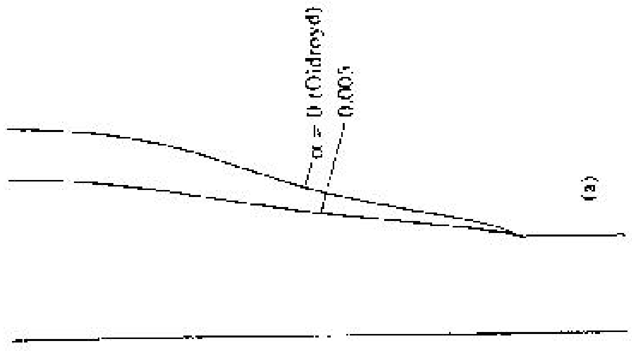
Fig. 9. Comparison of vorticity contourlines in viscoelastic flow with and without inertia: from the axis of symmetry to the wall, the values of $\omega d_{en}/V_{en}$ are given by $(0.8 + n1.6)$ with $n = 0, \ldots, 4$; a) Inertial flow, $We = 0.7$ and $Re = 24.1$; the critical line is plotted by the dashed line; b) Creeping flow, $We = 0.7$ and $Re = 0$

Giesekus fluid

- Non linear contribution in the Maxwell Model:

$$\text{Equation model}: \left(I + \frac{\alpha\lambda}{\eta}\sigma_{ij} \right)\sigma_{ij} + \lambda\sigma_{ij,t} = \eta d_{ij}$$

- Influence on the results:



Importance of d_{en}

- Experiments done with different fluids (E changes)

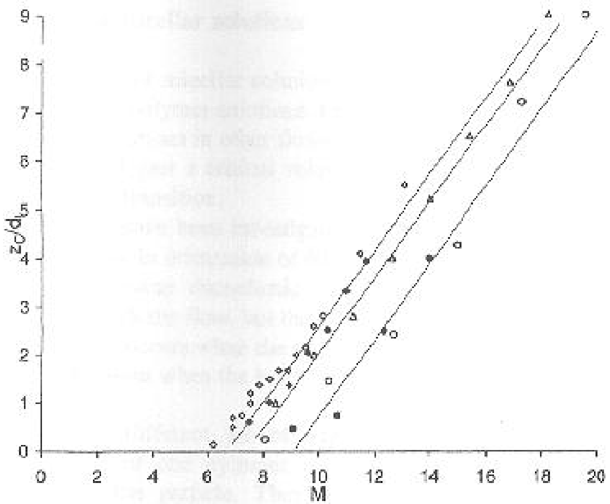


Fig. 8. Vertical location of the inflection point of the jet profile vs. the viscoelastic Mach number before exit. Each symbol refers to a different experiment: (open diamonds) d_i=0.60 mm, Φ=0.005, E=0.1; ◆ d_i=0.60 mm, Φ=0.007, E=5; ○ d_i=0.31 mm, Φ=0.005, E=0.5; • d_i=0.31 mm, Φ=0.005, E=20; d_i=0.40 mm, Φ=0.005, E=0.2.

Conclusion

- Delayed die swell may occur in any viscoelastic solution
- It is a critical phenomenon
- Numerics show that inertia induces a change from subcritical to supercritical conditions
- Critical Mach number depends on the diameter, M_{cr} increases when d_{en} decreases.
- Contradictions for the effects of E.