Experiments and numerical simulations of velocity overshoots in gradual planar contractions: the "cat's ears" effect.

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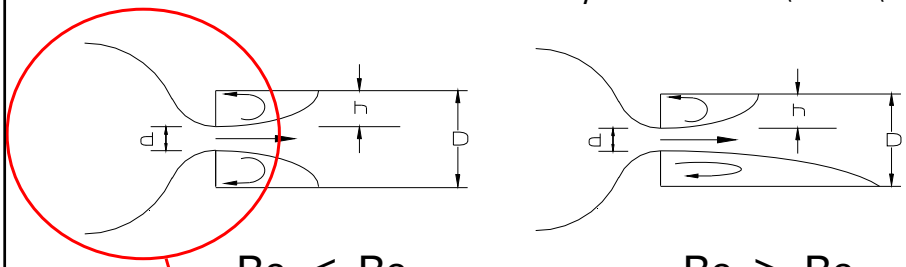
Outline - Experiments

- Previous work – what are "cat's ears"?
- Current study
- Experimental arrangement
- Working fluids and rheological characterisation
- Newtonian results
- Polyacrylamide (PAA) results
- Xanthan gum (XG) results

Previous work {Poole, Escudier & Oliveira, *Proc Roy Soc* 2005}

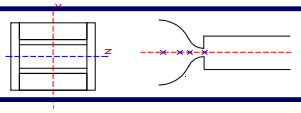
- Interested in examining effects of viscoelasticity on bifurcation know to occur in Newtonian sudden *expansion* flows (Re ≈*O*(10))

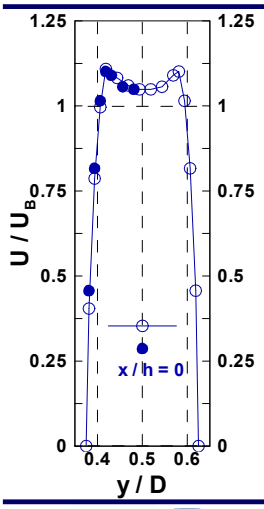


$Re < Re_{cr}$ $Re > Re_{cr}$

- Observed interesting inlet velocity profile

"Cat's ears"



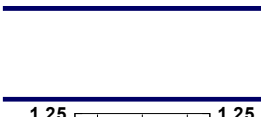


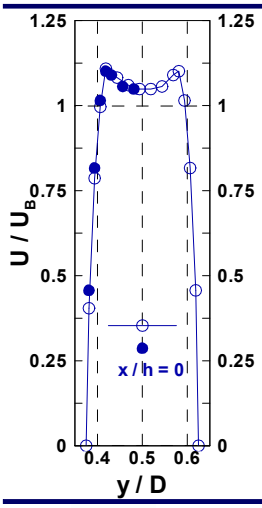
8:1:4 gradual contraction-sudden expansion

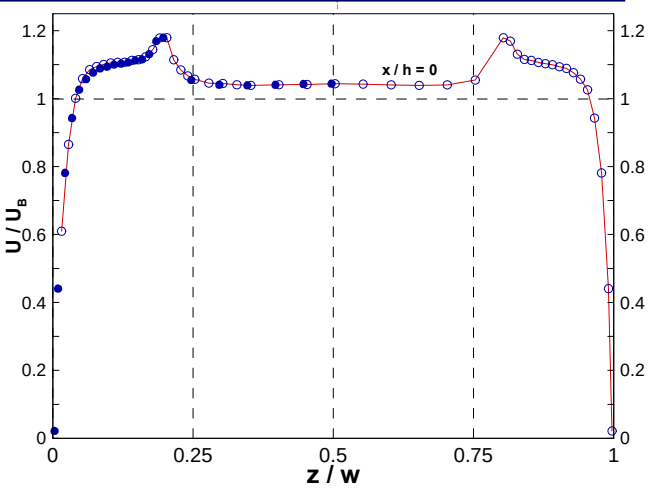
500 ppm polyacrylamide

Re ≈ 120 De ≈ 1.2

“Cat’s ears”

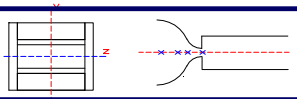


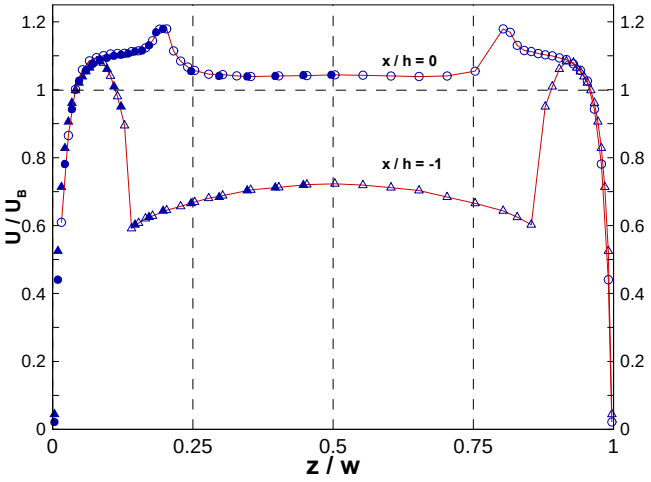




Complex flows of complex fluids, Liverpool
March 17 -19th 2008

“Cat’s ears”





Complex flows of complex fluids, Liverpool
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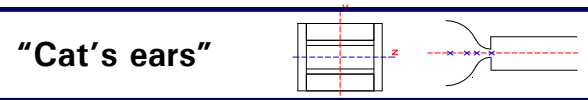

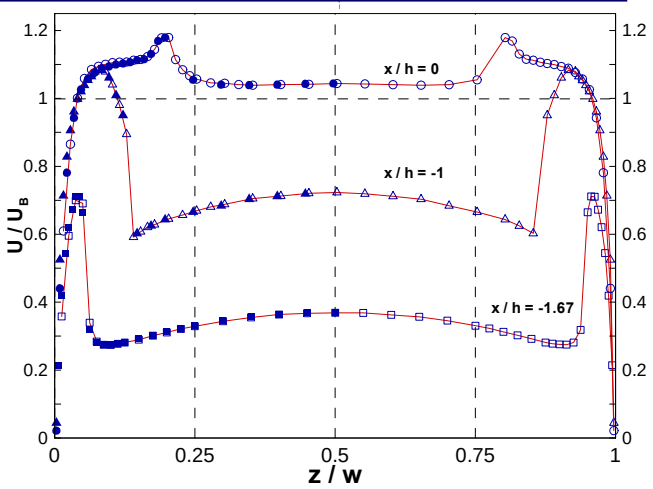

Complex flows of complex fluids, Liverpool
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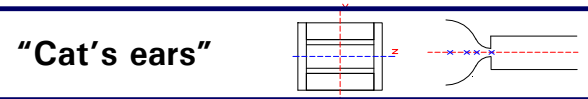
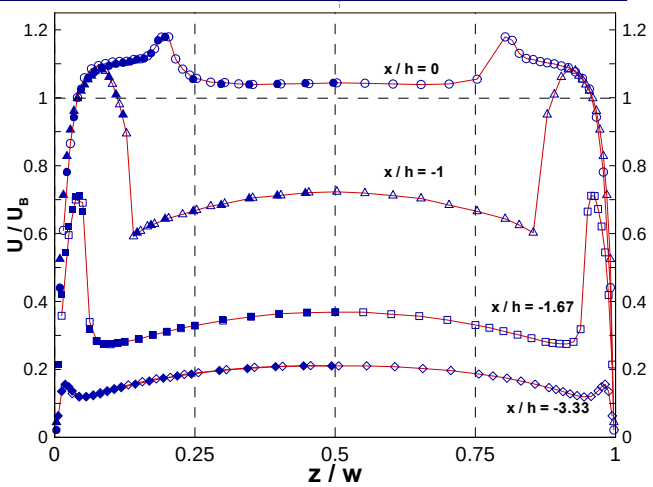
“Cat’s ears”





Complex flows of complex fluids, Liverpool
March 17 -19th 2008

Current study (& future plans)

Removal of the sudden expansion

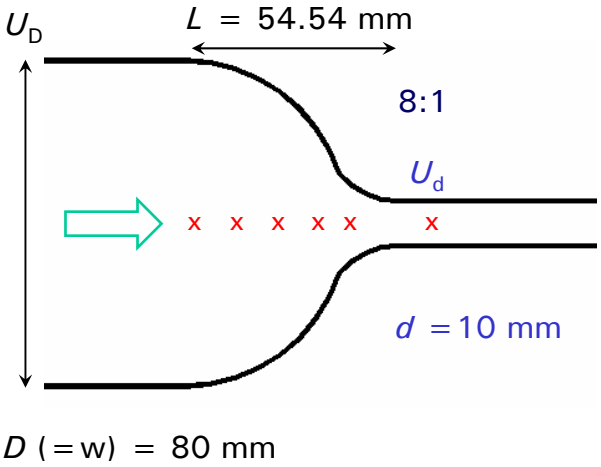
- "Cat's ears" still present?
- Allow simulations at higher De? Role of N_2?
- 3D benchmark flow?

Investigate type of polymer

- "Flexible" polyacrylamide, polyethylene oxide
- "Rigid" or "semi-rigid" xanthan gum, scleroglucan

Pressure-drop measurements and lower contraction ratio

Experimental arrangement



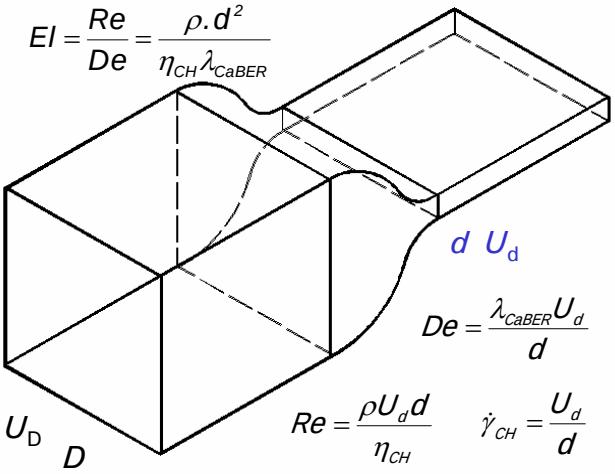
80 x 80 mm square duct to 80 x 10 mm rectangular duct

Inlet length 30 D

Gradual contraction identical in shape to previous study

Experimental arrangement

$$El = \frac{Re}{De} = \frac{\rho . d^2}{\eta_{CH} \lambda_{CaBER}}$$



80 x 80 mm square duct to 80 x 10 mm rectangular duct

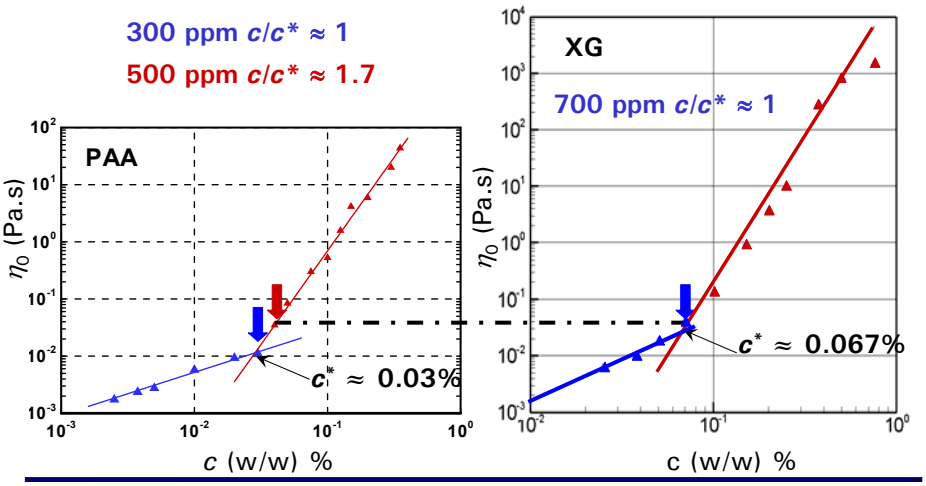
Inlet length 30 *D*

Gradual contraction identical in shape to previous study

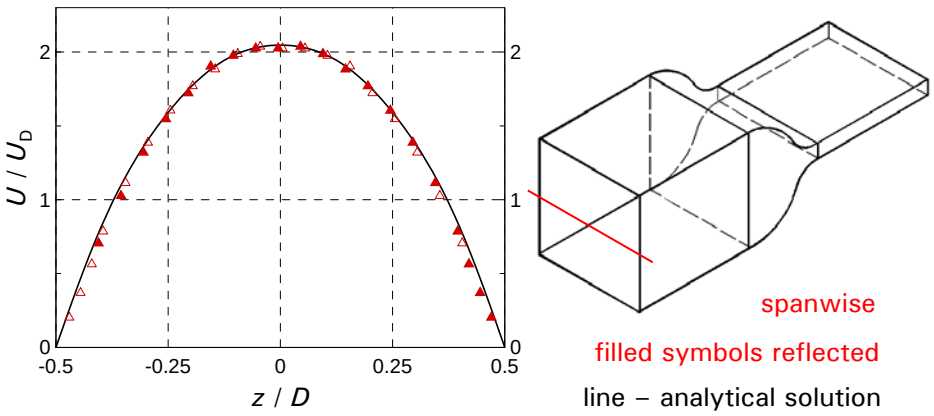
Working fluids and rheological characterisation

- Glycerine – Newtonian acts as control
  – Numerical simulations exact (Navier Stokes Eqns)
- Polyacrylamide (PAA) in water
  – Separan AP 273 E
- Xanthan gum (XG) in water
  – Keltrol TF from Kelco
- Steady shear
- Small amplitude oscillatory shear (linear)
- Capillary break-up extensional rheometer data (including high-speed camera images)

Polymer concentrations used



Newtonian experiments and simulations (Re = 115)



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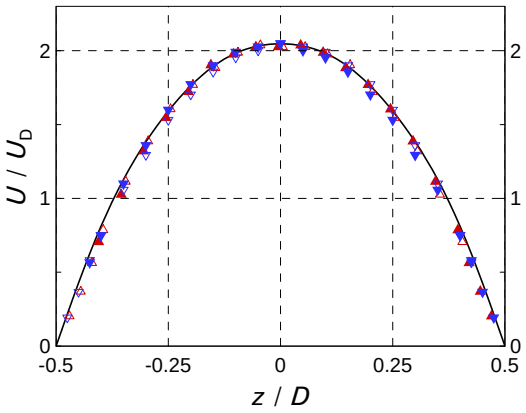
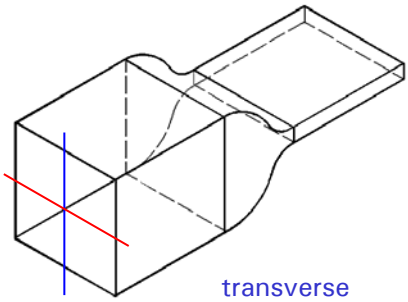


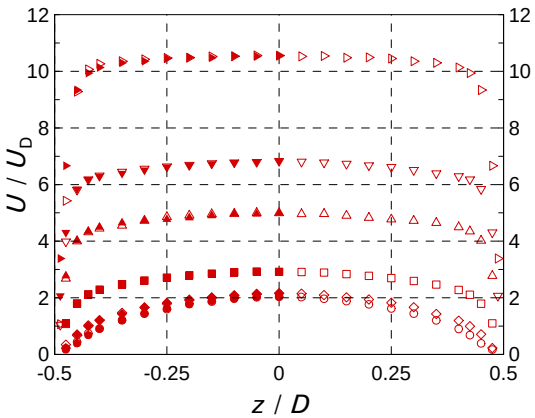


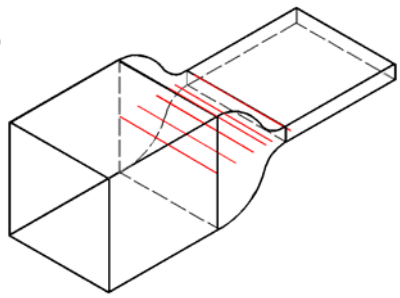
transverse

filled symbols reflected

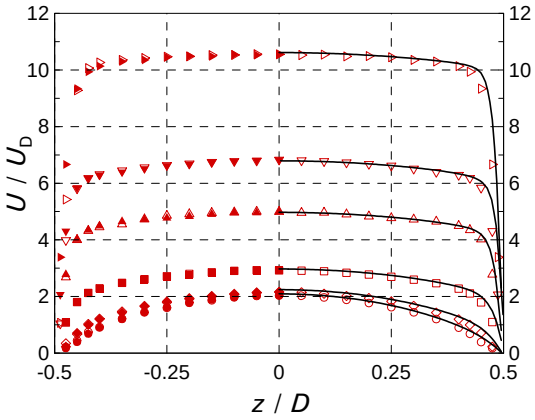
line – analytical solution

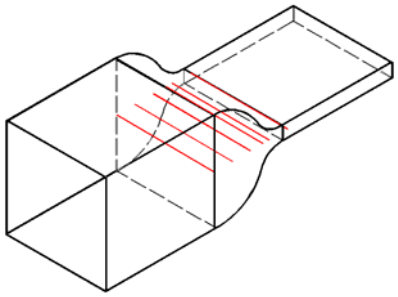
Newtonian experiments and simulations (Re = 115)





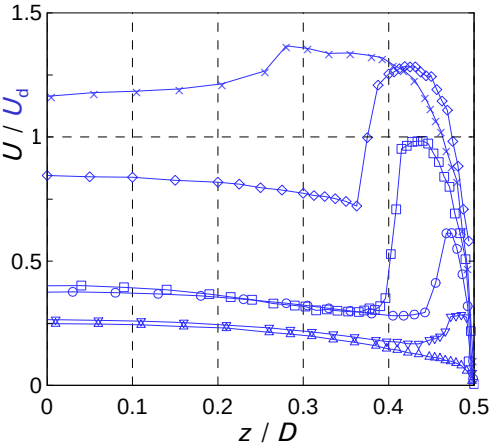
Newtonian experiments and simulations (Re = 115)

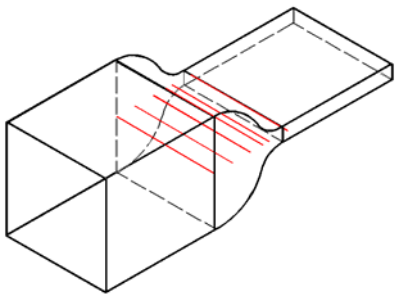




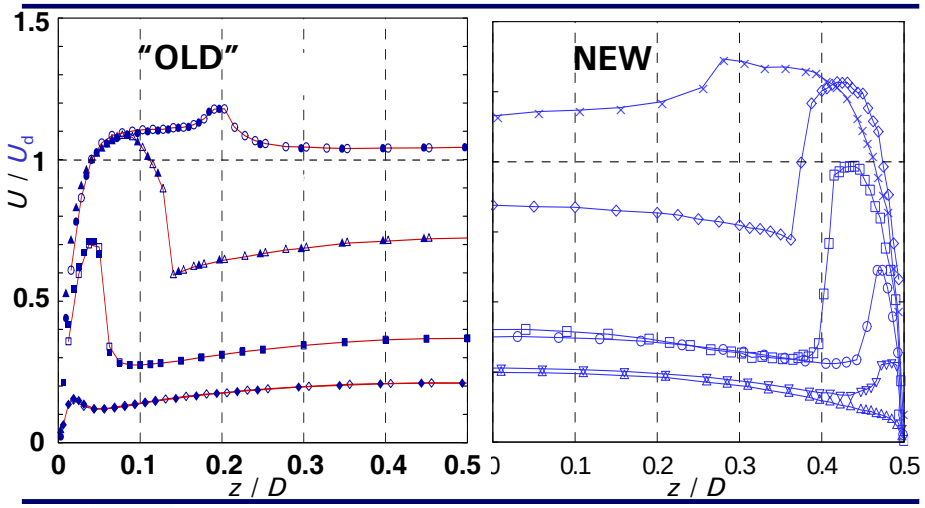
lines – simulation

500 ppm PAA ($c/c^* \approx 1.7$) ($Re = 120$, $De = 1.2$)



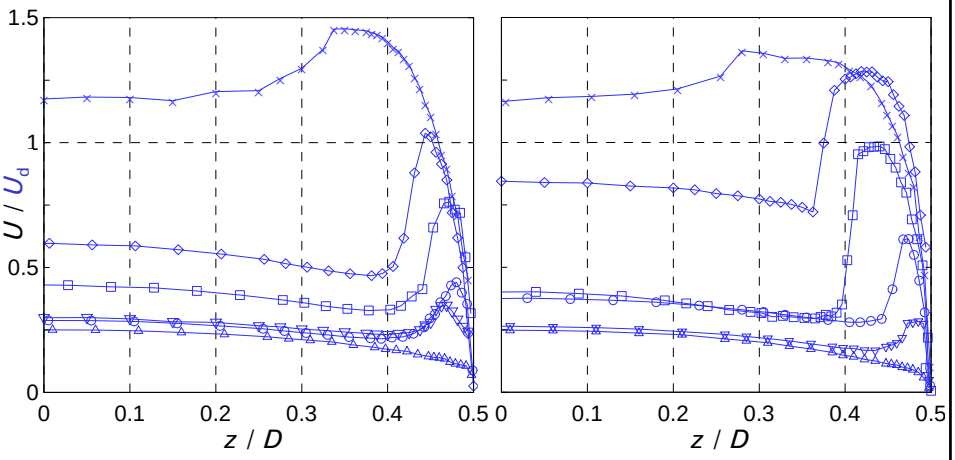


500 ppm PAA ($c/c^* \approx 1.7$) ($Re = 120$, $De = 1.2$)



500 ppm ($c/c^* \approx 1.7$) $El = 0.01$

$Re = 50$, $De = 0.52$ $Re = 120$, $De = 1.2$

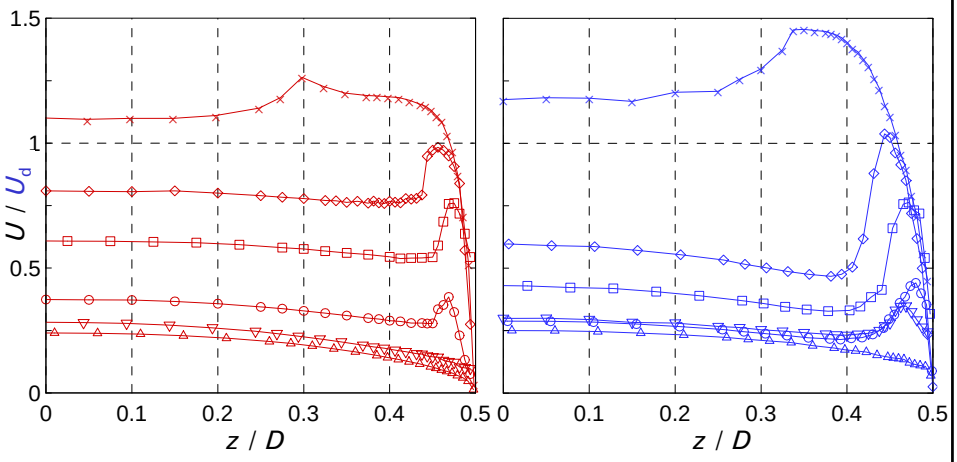


300 ppm ($c/c^*\approx1.0$) $El = 0.0017$

$Re = 370$, $De = 0.52$

500 ppm ($c/c^*\approx1.7$) $El = 0.01$

$Re = 50$, $De = 0.52$

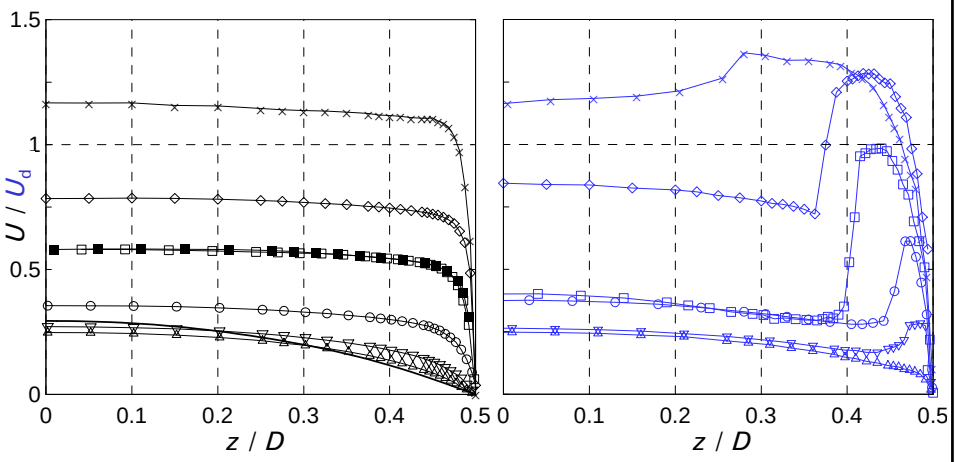


700 ppm ($c/c^*\approx1.0$)

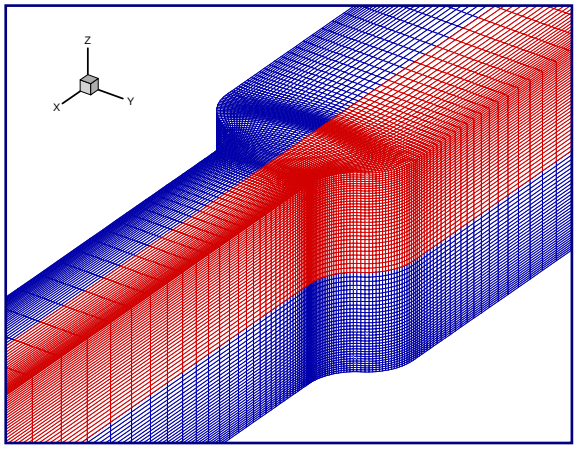
XG $Re = 130$, $De \approx 0$ (?)

500 ppm ($c/c^*\approx1.7$)

PAA $Re = 120$, $De = 1.2$

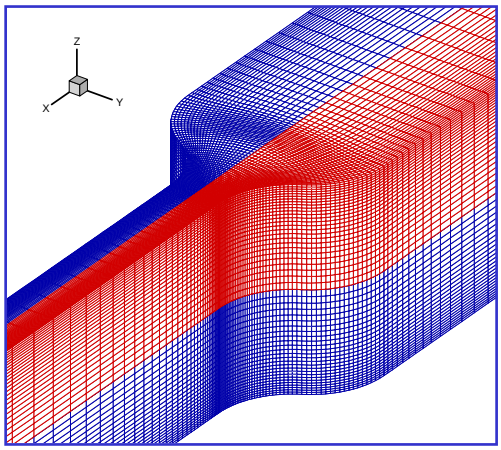


Computational mesh – *CR* = 2 (zooming view)



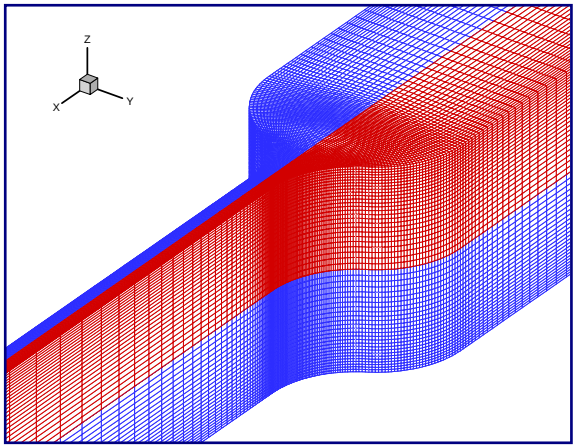
1 763 840 DOF

Computational mesh – *CR* = 4 (zooming view)



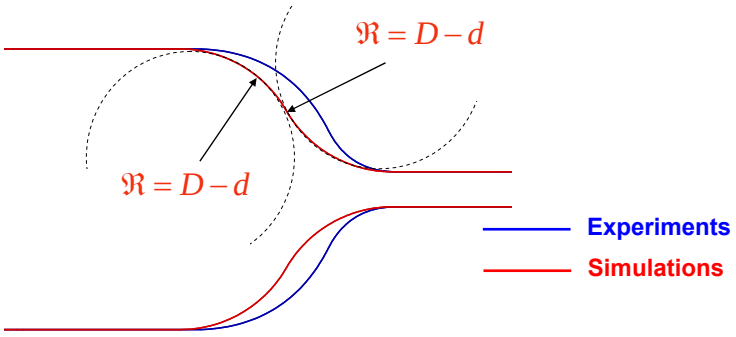
1 311 440 DOF

Computational mesh – *CR* = 8 (zooming view)



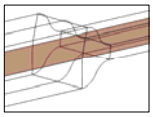
1 649 440 DOF

Flow geometry (*CR* = 8)

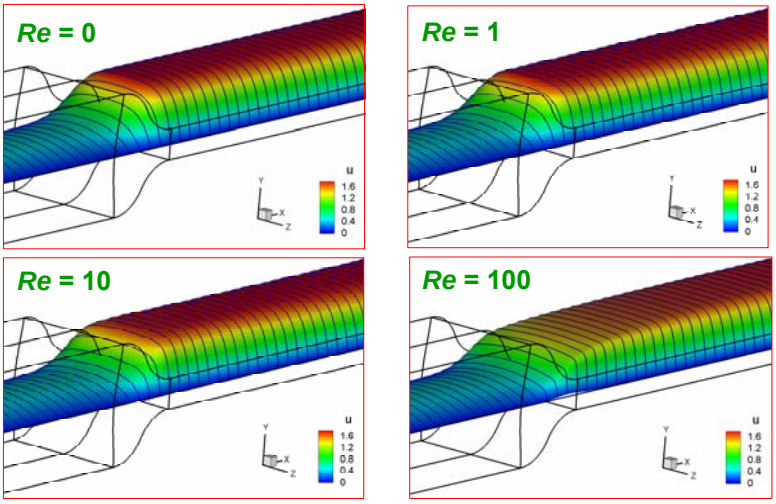


- **No flow separation** ☺
- **Constant wall radius of curvature** ☺
- **Smooth flow** ☺
- **Variable strain rate, but easier to estimate (no recirculation)**

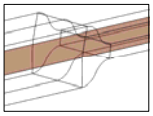
Effect of Inertia – Newtonian Fluid (CR = 4)



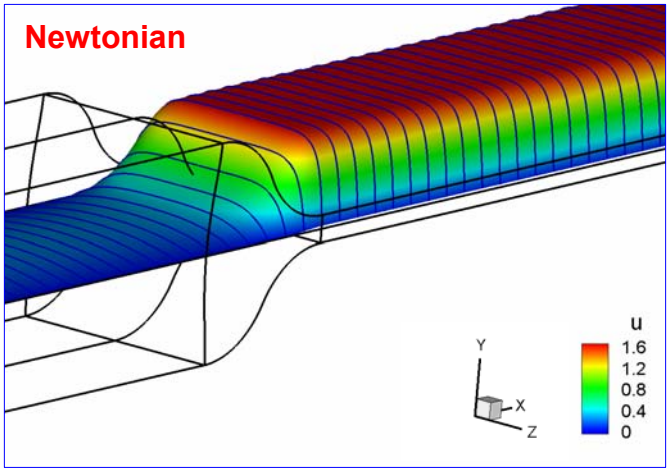
Axial velocity in *x*-*z* plane (neutral) *y* = 0



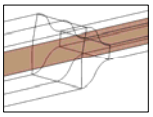
Effect of *De* – UCM Fluid (*CR* = 8) *Re* = 0



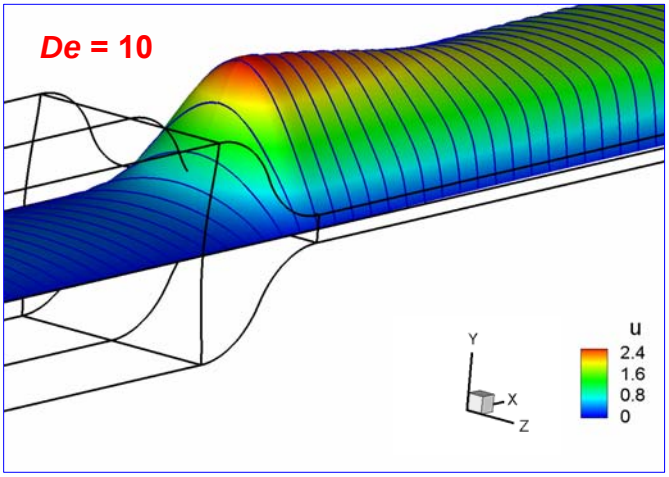
Axial velocity in *x*-*z* plane (neutral) *y* = 0



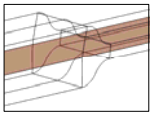
Effect of *De* – UCM Fluid (*CR* = 8) *Re* = 0



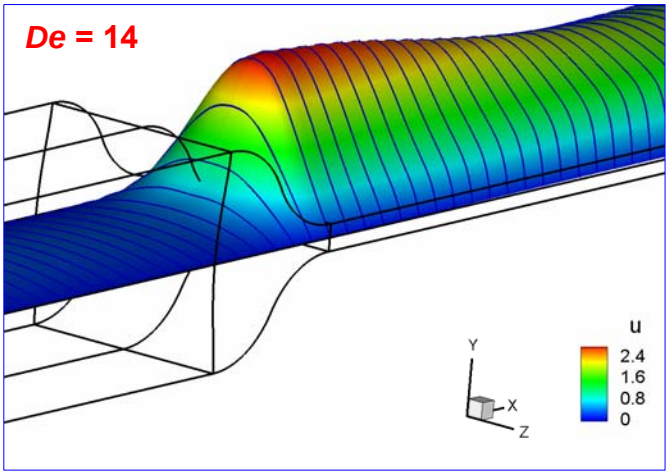
Axial velocity in *x*-*z* plane (neutral) *y* = 0



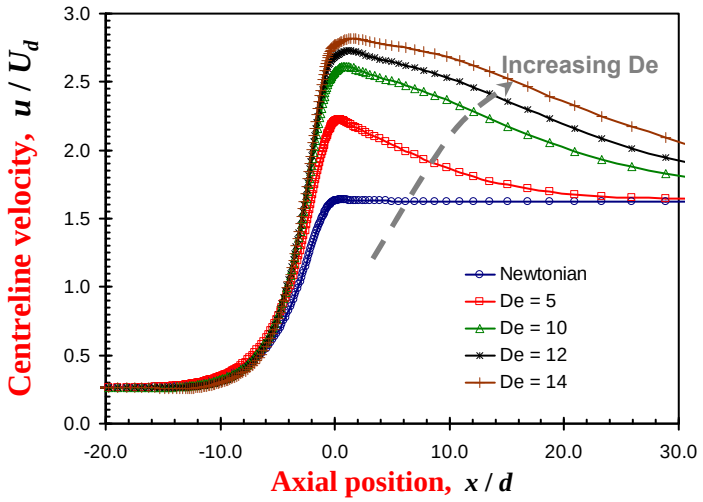
Effect of *De* – UCM Fluid (*CR* = 8) *Re* = 0



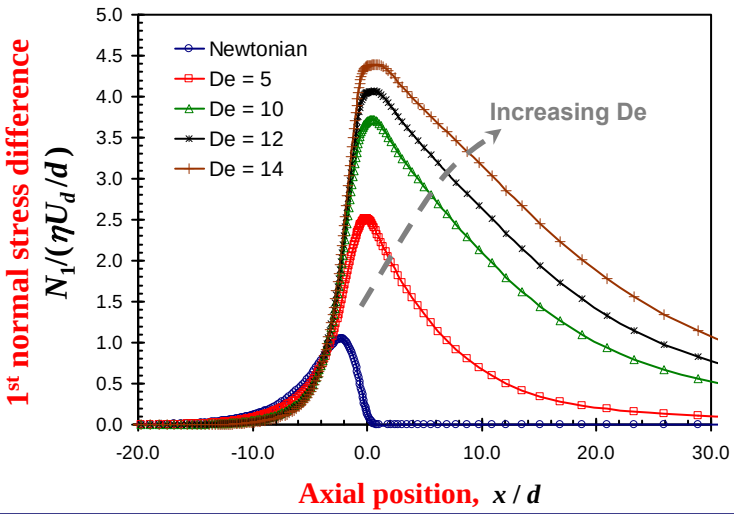
Axial velocity in *x*-*z* plane (neutral) *y* = 0



Effect of *De* – UCM Fluid (*CR* = 8) *Re* = 0

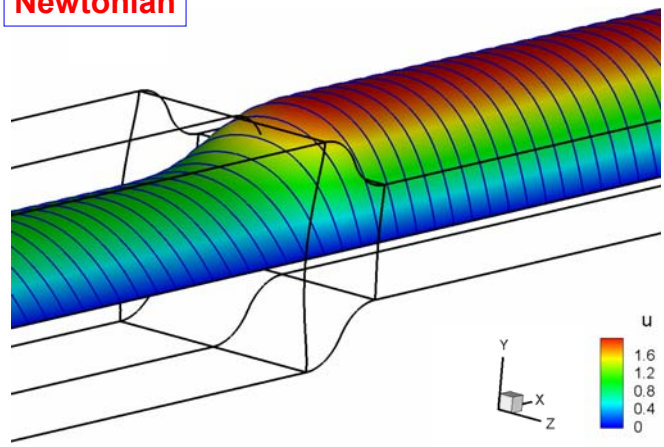


Effect of *De* – UCM Fluid (*CR* = 8) *Re* = 0



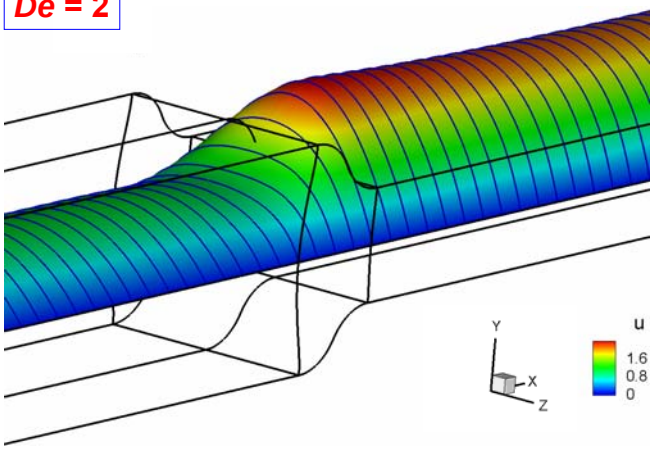
Effect of *De* – UCM Fluid (*CR* = 2) *Re* = 0

Newtonian



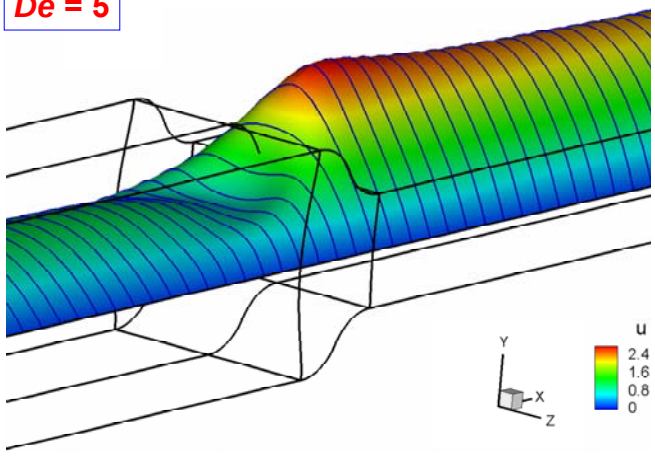
Effect of *De* – UCM Fluid (*CR* = 2) *Re* = 0

***De* = 2**

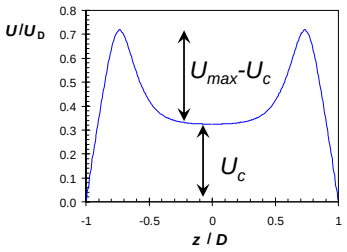


Effect of *De* – UCM Fluid (*CR* = 2) *Re* = 0

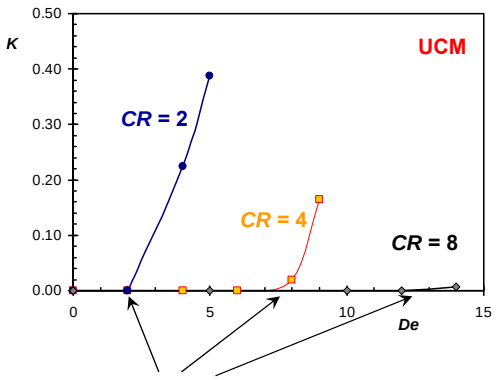
De = 5



Quantification of cat's ears

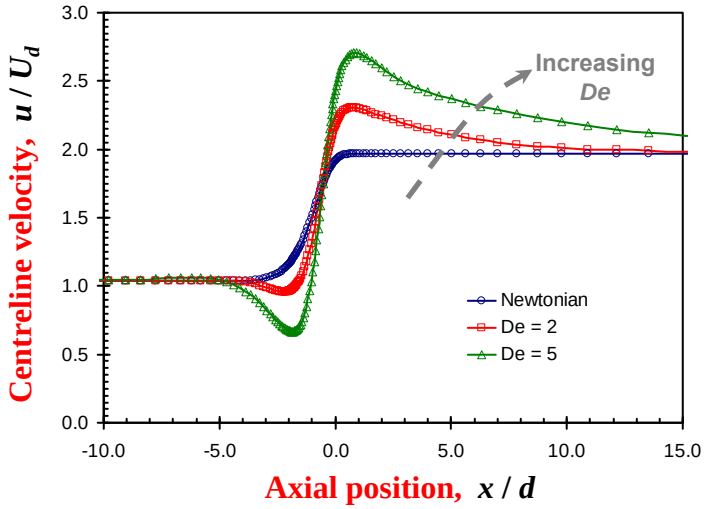


$$K = \frac{U_{max} - U_c}{U_c}$$

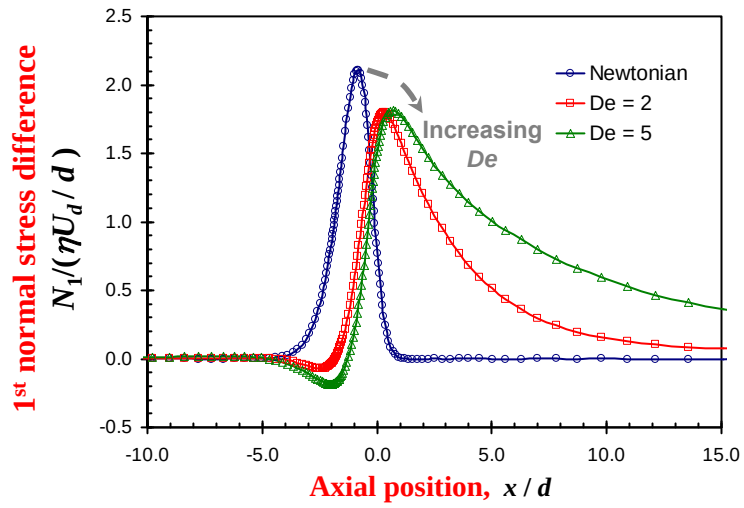


Critical *De* for onset of cat's ears

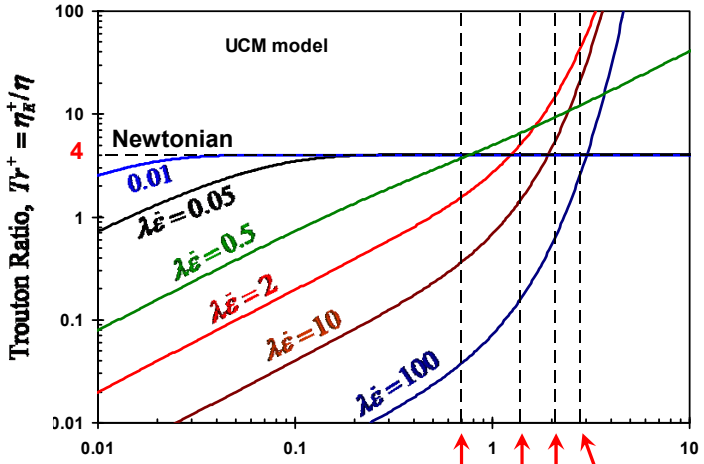
Effect of *De* – UCM Fluid (*CR* = 2) *Re* = 0



Effect of *De* – UCM Fluid (*CR* = 2) *Re* = 0



Trouton Ratio (UCM model)

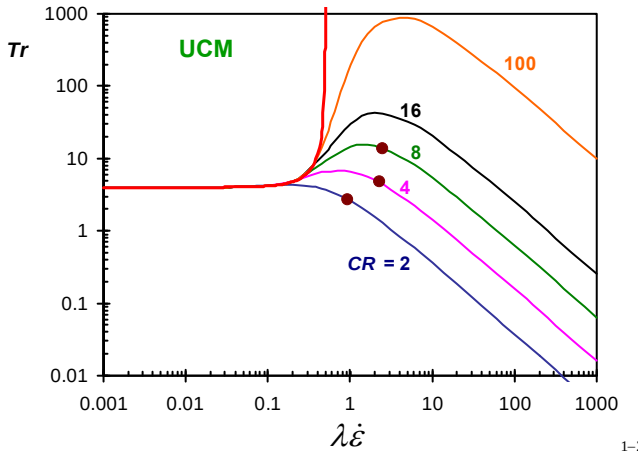


Hencky strain, $\varepsilon_H = \dot{\varepsilon}\, t$

CR = 2 4 8 16

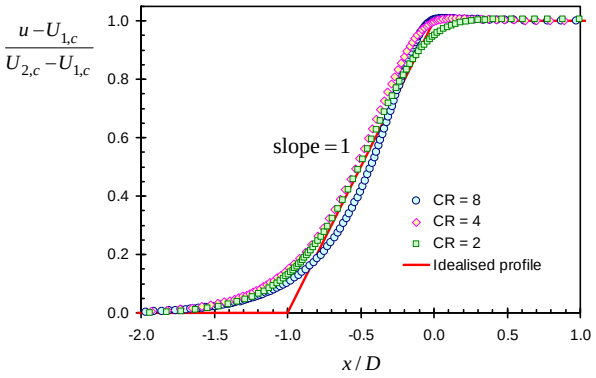
$$CR = \exp(\varepsilon_H)$$

Trouton Ratio (UCM model)



$$Tr = \frac{4}{(1-2\lambda\dot{\varepsilon})(1+2\lambda\dot{\varepsilon})} - \frac{CR^{\frac{1-2\lambda\dot{\varepsilon}}{\lambda\dot{\varepsilon}}}}{1-2\lambda\dot{\varepsilon}} - \frac{CR^{\frac{1+2\lambda\dot{\varepsilon}}{\lambda\dot{\varepsilon}}}}{1+2\lambda\dot{\varepsilon}}$$

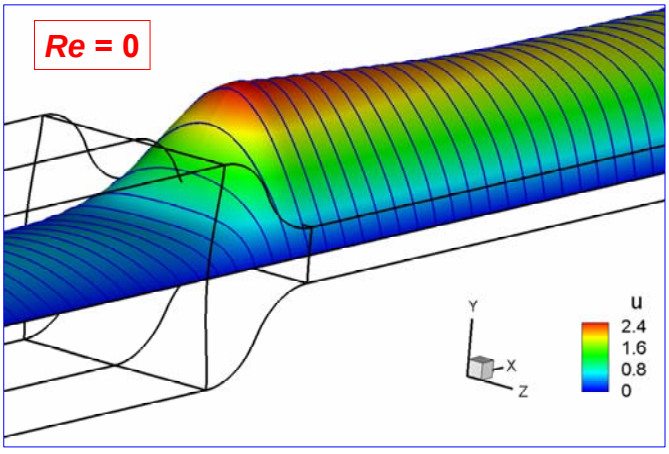
Strain-rate estimation (Newtonian model – creeping flow)



$\dot{\varepsilon} = \frac{U_{2,c} - U_{1,c}}{D}$ is indeed a good **estimate** of the strain-rate

Effect of Inertia – UCM Fluid (*CR* = 4)

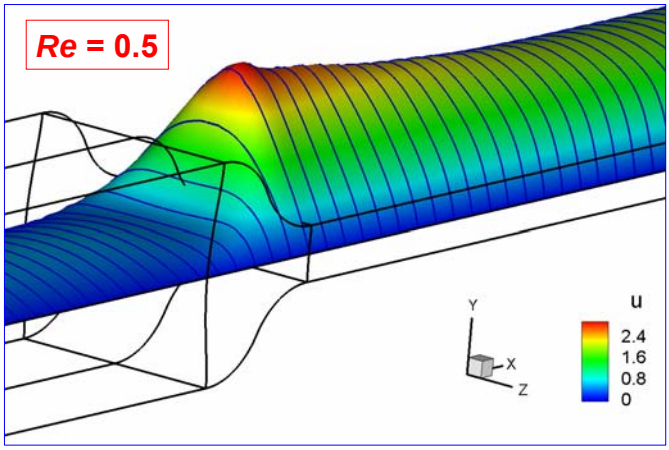
***De* = 6**



Effect of Inertia – UCM Fluid (*CR* = 4)

De = 6

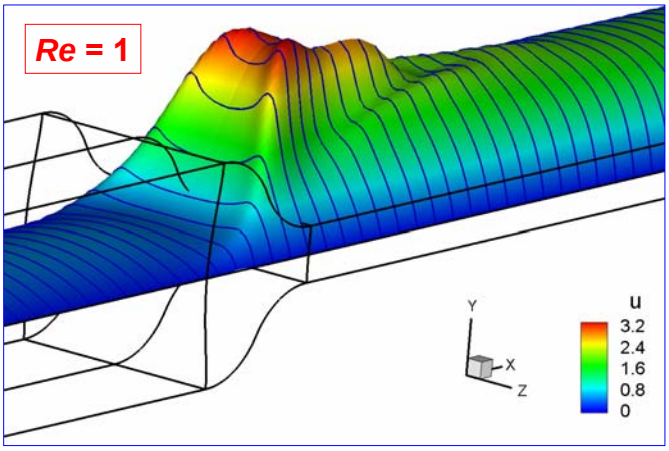
Re = 0.5



Effect of Inertia – UCM Fluid (*CR* = 4)

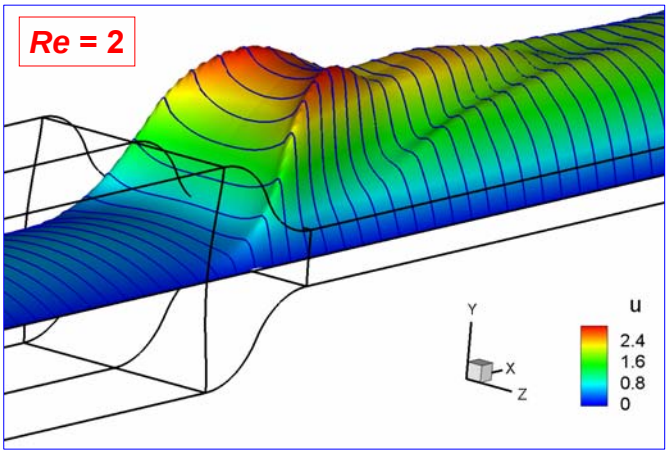
De = 6

Re = 1



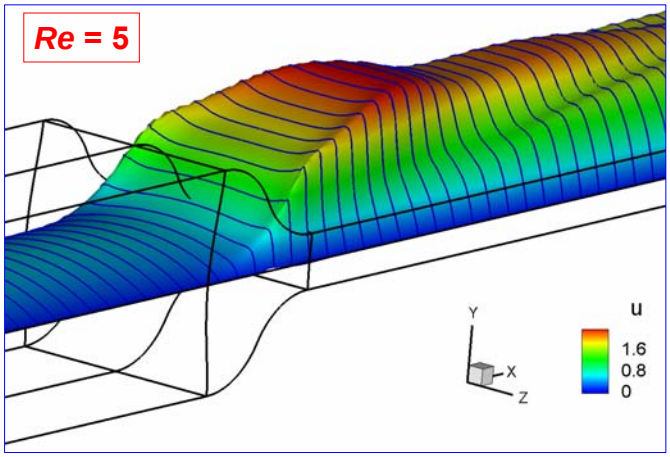
Effect of Inertia – UCM Fluid (*CR* = 4)

De = 6



Effect of Inertia – UCM Fluid (*CR* = 4)

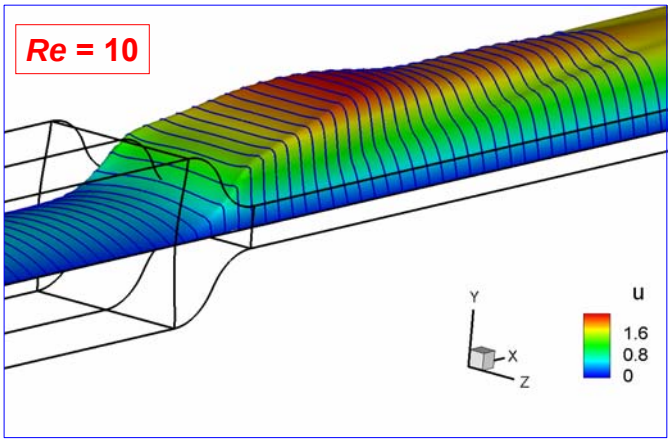
De = 6



Effect of Inertia – UCM Fluid (*CR* = 4)

De = 6

Re = 10

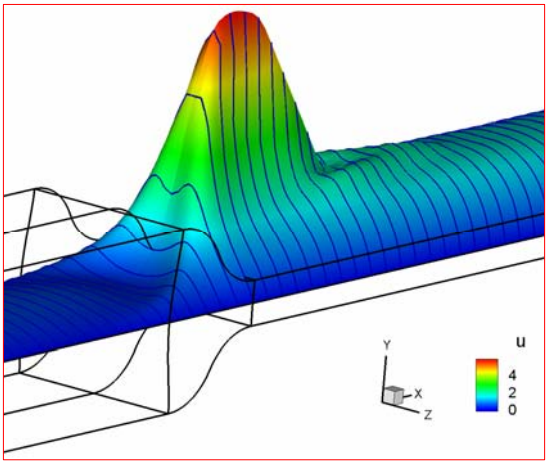


SPTT Fluid ε = 0.02 (*CR* = 4)

(no solvent)

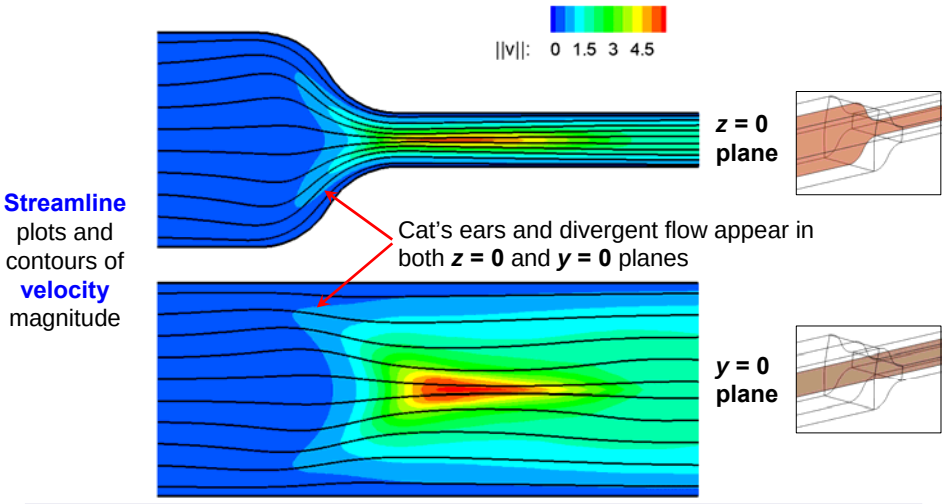
De = 16

Re = 0.5



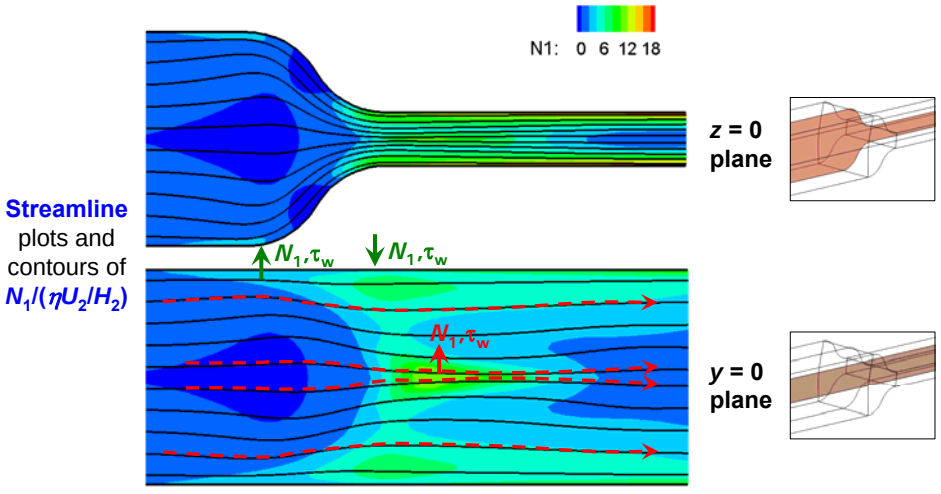
SPTT Fluid $\varepsilon = 0.02$ ($CR = 4$) (no solvent)

$De = 16$ $Re = 0.5$



SPTT Fluid $\varepsilon = 0.02$ ($CR = 4$) (no solvent)

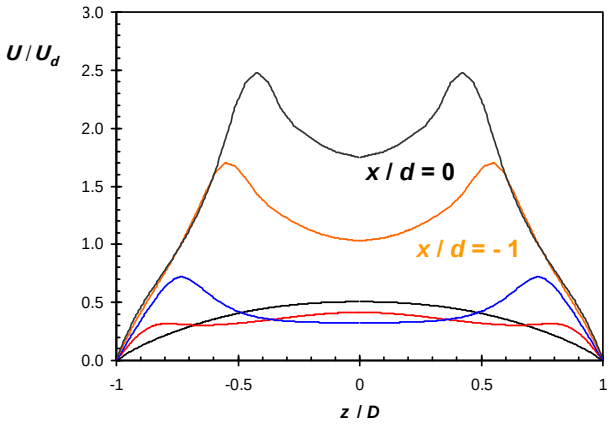
$De = 16$ $Re = 0.5$

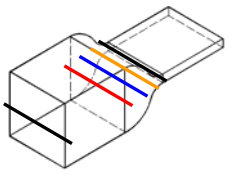


SPTT Fluid $\varepsilon = 0.02$ ($CR = 4$) (no solvent)

$De = 16$ $Re = 1$

Upstream velocity profiles





Conclusions

Removal of the expansion

- Cat's ears still present
- Allows computations at higher *De* (no geometric singularity)
- The numerical simulations are able to (qualitatively) capture the phenomena

Ongoing/Future Work

- Computations with the exact rheology of the fluids (multi-mode models are necessary) in the experimental geometry
- Identify and quantify the cat's ears phenomena within the *De*/*Re* parameter space

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- FCT (Portugal) and FEDER for funding (project POCI/EQU/56342/2004)
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Thank you!

Any Questions?