Flow of Some Carboxymethylcellulose Solutions Through Abrupt Axisymmetric Contractions. Experimental Study and Modelling of Shear Thinning and Elongational Effects

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Abstract:
The focus of this paper will be on the modelling and simulation of contraction flow, with marked aspect ratio $\beta = 6, 9, 12$. Two fluid families are considered: a glycerol Newtonian solution and carboxy-methyl-cellulose (CMC) solutions which present particular rheological properties. Their shear thinning character are modelled by a Cross formula over a large scale of shear rates. The elongational properties are taken via a simplified Ericksen model into account. Experimental velocity profiles are determined using the Laser Doppler Anemometry (L.D.A) technique. They are found to be in good agreement with numerical velocity profiles obtained using a finite volume method with extra source terms traducing the particular rheological behaviour proposed here. The simulations allow to determine the different values of an elongational parameter μ_3. Then, some numerical results concerning the total energy losses are presented using the usual concept of the equivalent length.

Zusammenfassung:
Den Schwerpunkt dieses Artikels bildet die Modellierung und die Simulation der Düseneinlaufströmung bei vorgegebenen Längenverhältnissen, b = 6, 9, 12. Zwei Klassen von Flüssigkeiten werden berücksichtigt: eine Newtonsche Glycerin-Lösung und verschiedene Carboxyl-methyl-cellulose(CMC)-Lösung, welche besondere rheologische Eigenschaften aufweisen. Ihre strukturviskosen Eigenschaften werden mit einer Gleichung nach Cross über einen großen Scherratenbereich modelliert. Die Dehneigenschaften werden mit Hilfe eines vereinfachten Erickson-Modells erfasst. Experimentelle Geschwindigkeitsprofile werden unter Benutzung der Laser-Doppler-Anemometrie (L. D. A.) bestimmt. Diese werden durch numerisch ermittelte Geschwindigkeitsprofile bestätigt, wobei eine Finite-Elemente-Methode mit zusätzlichen Quelltermen benutzt wurde, die das besondere rheologische Verhalten, das hier vorgeschlagen wird, beruecksichtigen. Die Simulationen erlauben die Bestimmung der verschiedenen Werte eines Dehnparameters μ_3. Danach werden einige numerische Resultate betreffend des Gesamtenergieverlustes vorgestellt, wobei das übliche Konzept der äquivalenten Längen zu Grunde gelegt wird.

Résumé:
L'objet de ce papier est la simulation numérique et la modélisation de l'écoulement de solutions de carboxymethyl-cellulose (CMC) au travers de contractions brusques axisymmétriques de rapports d'aspect élevés $\beta = 6, 9, 12$. Deux familles de fluides ont été considérées: une solution newtonienne de glycérol pour calibration ainsi que diverses solutions de CMC aux propriétés rhéologiques particulières. Le caractère rhéofluidifiant a été pris en compte par le biais du modèle de Cross permettant ainsi l'étude sur un large domaine de taux de cisaillement. Un modèle d'Ericksen simplifié a été utilisé pour rendre compte des propriétés élongationnelles des fluides. Des profils expérimentaux de vitesse ont été déterminés par la technique de vélocimétrie laser à effet Doppler. Ils sont en bon accord avec les résultats numériques obtenus par une méthode de volumes finis. La simulation permet de déterminer les valeurs d'un paramètre physique μ_3 traduisant les propriétés élongationelles. Enfin, des résultats numériques, concernant la perte de charge totale, sont présentés en faisant usage du concept traditionnel de longueur équivalente.

Key words: shear thinning, elongational flow, equivalent length

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The parameter μ_{w2} is the apparent viscosity calculated at the wall for an established regime in the downstream pipe. As expected, the equivalent length hardly depends on the β ratio. All our results appear to be compatible with a slope $\Delta L_{eq}/\Delta Re_{down}$ about 0.056. The initial value about 0.35 can not be defined with the same accuracy. These results could be compared to the formula proposed by Boger L_{eq} = 0.589 + 0.0709 Re for Newtonian fluids with β = 4 and also to results obtained by Kim et al. [3]. They considered the Carreau model and a constant viscosity scaling. The different slopes may be explained by the rheological model and more particularly by the particular choice for the expression of the Reynolds number. In fact, due to the important values of β, the wall viscosity μ_{w2} may be very different from the viscosity calculated at the inlet section.

5 CONCLUSION

For the different CMC solutions tested, a simplified Ericksen model has been introduced. The shear thinning character of the fluids and also the fluid/fibres interactions are taken into account. Indeed, the various stress components are modified so as to enhance the effect of the elongational rate. By comparison to experimental velocity profiles obtained at various axial positions and as well as by rheological tests, it was possible to determine optimal values for the model parameter μ_3. This physical parameter is probably a function of the shear and elongational rates, but there is not enough experimental data to draw a conclusion regarding this point. By means of numerical simulations, the influence of the orientation field has been tested. Within the Reynolds numbers interval considered, the impact of orientation on the u velocity on the axis is not really marked. So a simplification was proposed which leads to a very simplified version with an important convergence domain. The total energy losses are treated using the equivalent length notion. As far as the two fluids and the three contraction ratios are considered, a unique formulation is acceptable.

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NOMENCLATURE

$\mathbf{D}$ = strain rate tensor
g = acceleration of gravity
G' = storage modulus
G'' = loss modulus
$\mathbf{I}$ = identity matrix
I_2 = second invariant of D
L_1 = large pipe length
L_2 = small pipe length
L_{eq} = equivalent length
n = rheological index
N_1 = first normal stress difference
$\mathbf{p}$ = local orientation vector
p_r, p_θ, p_x = $\mathbf{p}$ components
P = Isotropic pressure
r = radial position
R_1 = large pipe radius
R_2 = small pipe radius
Re_{up}, Re_{down} = upstream and downstream Reynolds numbers
u, v = axial and radial velocity components
U_{up}, U_{down} = mean upstream an downstream velocities
x = abscissa along axial direction
$\alpha_{up}, \alpha_{down}$ = kinetic energy coefficients
β = contraction ratio
$\Delta P, \Delta P_1, \Delta P_2$ = pressure variations
Δ_x, Δ_r = characteristic lengths of the measuring volume
$\dot{\epsilon}$ = elongational rate
$\dot{\gamma}$ = shear rate
λ = Cross model parameter
μ_o = zero shear viscosity in the Cross model
$\mu_1, \mu_2,, \mu_3, \mu_4$ = rheological parameters of the Ericksen model
ρ = density
τ = stress tensor
$\tau^N, \bar{\tau}$ = purely viscous and extra parts of the stress tensor
μ_{w2} = wall viscosity for the downstream pipe
τ_{w2} = wall shear stress for the downstream pipe
θ = polar angle
ω = pulsation

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