A Numerical Model of Yield Stress Fluid Dynamics in a Mixing Vessel

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Received: 18.2.2002, Final version: 17.7.2002

Abstract:
A numerical study is conducted on the behaviour of yield stress fluids in a mixing vessel equipped with anchor agitator in laminar regime. It is shown that extending a standard Carreau model of shear thinning fluid is a suitable practice. Validations versus Couette flow analytical solution are satisfactory. Main features of local hydrodynamics and global power consumption are described for a 2D flow. Significant changes in the flow pattern are observed for low inertia and high yield stress and the results are considered as guidelines for further laboratory experiments.

Zusammenfassung:
Wir führen numerische Berechnungen zum Verhalten von Fluiden mit Fliessgrenze in einem Mixer mit verankertem Rührer im laminarem Regime aus. Mit Hilfe eines erweiterten Standard-Carreau-Models für scherverdünnende Fluide lassen sich die Ergebnisse gut beschreiben, und es wird mit analytischen Berechnungen für eine Couette-Stroemung verglichen. Wir beschreiben die wesentlichen Eigenschaften der lokalen Hydrodynamik und globalen Energiebilanz in einer 2D-Strömung. Besondere Strömungsszenarien, die weitere Experimente motivieren, werden im Bereich geringer Inertialeffekte und grosser Haltespannungen beobachtet.

Résumé:
L'hydrodynamique d'une cuve munie d'un agitateur ancre est étudiée numériquement pour des fluides viscoplastiques en régime laminaire. Le modèle de Carreau est comparé aux modèles classiques utilisés numériquement pour la simulation d'écoulements de fluides de Bingham. Les tests réalisés sur un écoulement de Couette entre cylindres montrent qu'il est aussi performant. Les conséquences du caractère viscoplastique sur l'hydrodynamique ainsi que sur la puissance dissipée sont présentées sur un écoulement 2-D. Des modifications importantes de l'écoulement sont observées pour les régimes faiblement inertiels et / ou les forts seuils d'écoulement. Ces résultats constituent un support pour de futures expériences de laboratoire.

1 INTRODUCTION

A lot of industrial fluids are known for their non Newtonian properties. Liquid-liquid and solid-liquid dispersions are situations relevant to this category. For low and moderate concentrations, the behaviour usually becomes shear-thinning and a lot is known about hydrodynamics in mixing vessel for such fluids [1, 2]. However, large departures from this quasi-Newtonian behaviour are observed when concentration is higher. This situation is often encountered in practice because industrial trends are towards higher and higher concentration processes. As hydrodynamics plays a key role in the quality of mixing and therefore in the efficiency of the process, it is decisive to analyse influence of such a rheological behaviour.

Fluids with a "yield stress" are widely encountered in industry. Although the yield stress notion is to be employed cautiously, a lot of rheological data on industrial fluids exhibit very large

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that the flow pattern is drastically modified in the case of high yield stress and low inertia. The circulation is rather poor as indeed the major part of the power is put to rotate the anchor that has very little effect on the core of the reactor. The consequences on power consumption in the mixer are important and a generalized Reynolds number is used to take plasticity into account. Nevertheless this simplified numerical approach proves to be useful in order to anticipate on the behaviour of a yield stress fluid in a mixing vessel and provide useful information for design.

It is worthwhile noticing that these results have been established in a restricted range of flow parameters corresponding to moderate laminar numbers. The specific effect of yield stress is marked for high Hedström number and vanishes when the Reynolds number increases. To extend these results to practical situations, it should be necessary to define for the studied geometry a limiting curve in the (*He, Re*) or in the (*Bi, Re*) plane separating the regime of fully sheared flow to the one where quasi-solid displacements exist. Numerical computations can help finding this for a prescribed geometry if all conditions are respected. However, other effects can be involved such as slip at the wall or real fluids that are not pure Bingham ones.

ACKNOWLEDGEMENTS

The authors wish to thank the national and regional centres CINES and CALMIP for granting them in computing time. One of us (M.M.) was granted by the French "Ministère de l'Education Nationale" for preparing his doctoral thesis as part of the Joint Research Program FERMaT.

NOMENCLATURE

Bi: Bingham number
c: clearance between the impeller and the vessel bottom
D: impeller diameter
$\mathbf{D}$: strain rate tensor
D_a: shaft diameter
D_v: vessel diameter
e: impeller thickness
H: liquid height
He: Hedström number
H_v: vessel height
K_p: geometric constant for a mixing system
K_s: Metzner-Otto constant for calculating shear rate
m: Papanastasiou model parameter
n: power-law index (Carreau model)
N: rotational speed of inner cylinder/impeller
N_p: power number
p: pressure
P: power consumption
r_o: radius of the yield surface
R_1: inner cylinder radius
R_2: outer cylinder/vessel radius
Re: Reynolds number
Re_g: generalised Reynolds number
V: velocity vector
V_r: radial velocity
V_θ: tangential velocity
$\dot{\gamma}$: shear rate
$\dot{\gamma}_c$: cut off shear rate (bi-viscosity model)
δ: Bercovier model parameter
η_{app}: apparent viscosity
η_o: cut off viscosity for low shear rate
η_∞: limiting viscosity at infinite shear rate
λ: Carreau model time constant
ρ: density
$\boldsymbol{\tau}$: stress tensor
τ_o: yield stress

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