Numerical Model for Laminar Flow in Agitated Vessel by tow Blades Impeller

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ABSTRACT
A large number of chemicals, biochemical or petrochemical industry operations are performed in stirred tanks or in mechanically agitated vessels. The optimum operating mode of these equipments requires a detailed knowledge of the hydrodynamic behavior induced by the agitator. In this piece of work the characterization of the laminar viscous fluid flow fields in a cylindrical stirred tank is agitated by inclined blades anchor agitator studied. The computational fluid dynamic (CFD) model based on an implicit fractional step scheme and control volume method was developed for the spatial discretization of the Navier-Stokes, formulated in Cartesian coordinates primitives variables (u, v, p, T) on unstructured triangular mesh. Some simulations of the flow around an anchor with straights blades allowed validating the used method. We have analyzed the influence of the tilt blades degree on the hydrodynamic flow behaviors, such as the stream function, the velocity field, the velocities components, and the power consumption. The comparison between some of the obtained results with literature data, have showed a satisfactory agreement.

1. INTRODUCTION

From raw material to the conditioning of the finished product, any production in the genius of the processes calls upon a coordinated succession of fundamental operations distinct and independent of the process itself which are called unit operations. Every process goes through a combination of a number of unit operations [1].

Many processes of industries generally face difficulties related to the implementation of non-Newtonian fluids such as polymer solutions, melted polymers, detergents, petroleum products, biological fluids and food products, when moved stirred or mixed. If the agitation is a unit operation aiming at promoting a physical process, such as homogenization or enhancement of heat transfer, predicting the power required for its implementation will be the primary concern.

Since the mixer is a reactor, more information on the fine structure of the flow will be essential. The agitation of these fluids into an industrial tank requires very high energy consumption where the optimization is a crucial problem.

This operation is often implemented to achieve intimate contact between different phases, to make them under the best conditions of mass and heat transfer. All processes in the industry must meet two major requests: to provide finished products of high quality on

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the one hand, a reduced cost taking into account the preservation of environment, on the other hand. These require two major points:

- To know and control all aspects involved in the process, particularly hydrodynamics.
- To take into account the character highly non-Newtonian, conditioning strongly the hydrodynamics.

Our work focuses exclusively on systems mechanically agitated by plan stirrers in this case the gate impeller in cylindrical tanks with flat bottom not chicaned.

The choice of these geometries has the advantage of generating a flow that can be considered as two-dimensional [2]. The gate agitators are especially suitable in the case of heat transfer at the wall [3-4]. Indeed, this impeller, having a small clearance to wall, and present the interest to locate their action near the heating walls. The gate agitator is often considered as an anchor of particular geometry [5-6]. In this study, it is assumed to consist of four vertical plane blades.

The flow regime is considered laminar and the fluid used is a viscoplastic of Bingham modeled by a double viscosity law. The difficulties of modeling the problem lie in the non-Newtonian behavior of the fluid.

There exist in contrast few results on viscoplastic fluid. We note in particular the works of Hirata et al [7] about the existence of a 'cavern' outside of which the fluid is not put into movement by the impeller, and Einz-Mozaffari et al [8] on the movement inside an agitated system containing paper pulp. Bertrand et al [9] conducted a numerical approach of an agitation system in Bingham fluid that allows highlighting the strong influence of the viscoplastic nature on hydrodynamics and power consumption. Curran et al [10] on their side studied experimentally the hydrodynamics and circulation time in a reactor with helical ribbon impeller. Anne-Archard et al [11] have proposed on the basis of a numerical study [2], a discussion of the criterion of Metzner and Otto on such flows.

We have undertaken a numerical simulation of hydrodynamics which is a key element of the control and process optimization. Its knowledge and mastery are therefore crucial to improve efficiency. To do this, we try to determine the influence of rheological properties of the fluid on these flows.

2 MODEL DESCRIPTION

The agitation of the viscoplastic fluid is done in a cylindrical tank of a diameter D equipped by a gate impeller of a diameter d. the geometry studied is shown in Figure 1.

The equations are made dimensionless by using for the lengths the diameter of the agitated tank (D=0.3), for the velocities the linear velocity at the wall vessel V= π DN.

Tank and anchor geometries chosen correspond to d/D=0.96, L/D=0.067, e/D=0.027 and da/D=0.023.

The Bingham model is used for viscoplastic behavior:

In this study, the problem consists from a full conductor of cylindrical shape attached to eddy current probe (see figure 1). The sample is a long cylindrical tube with constant properties.

$$D_{ij} = 0 \text{ for } \tau_{II} \leq \tau_0 \tag{1}$$

$$\tau_{ij} = 2\left(\frac{\tau_0}{\dot{\gamma}} + \eta_\infty\right) D_{ij} \text{ for } \quad \tau_{II} > \tau_0 \tag{2}$$

Where Dij is the strain rate tensor defined by:

$$D_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_i}{\partial x_i}\right) \tag{3}$$

$\dot{\gamma}$ The second invariant of the strain rate tensor:

$$\dot{\gamma} = \sqrt{2 D_{ij} D_{ij}} \tag{4}$$

And τ_{II} the second invariant of the stress tensor:

$$\tau_{II} = \sqrt{2 \tau_{ij} \tau_{ij}} \tag{5}$$

As can illustrated in equation (1), the ideal Bingham model shows a discontinuity for τ =τ0 that is at vanishing shear rates, the apparent viscosity in equation (2) becomes infinite, which causes difficulties in terms of numerical resolution. To overcome this problem, several modified versions of the original Bingham model have been proposed. These modified models are continuous and apply to both the yielded and unyielded regions. That is: they can be considered to be regularized versions of the discontinuous base model. The regularized models include: Papanastasiou [12], the bi-viscosity [13] and Bercovier and Engelman models [14]. In this contribution we are going to modeling the behavior law by a double viscosity model given by:

$$\eta(\dot{\gamma}) = \frac{\tau_0}{\dot{\gamma}} + \eta_\infty \quad if \quad \dot{\gamma} > \dot{\gamma}_c \tag{6}$$

$$\eta(\dot{\gamma}) \to \frac{\tau_0}{\dot{\gamma}} + \eta_\infty = \eta_0 \qquad if \qquad \dot{\gamma} \le \dot{\gamma}_c \tag{7}$$

This model is used by O'Donovan and Tanner [13] and Beverly and Taner [15], they have adopted a viscosity ratio equal to 1000 in order to obtain good results. It’s also used in investigations carried out by RAHMANI et al [16-17].

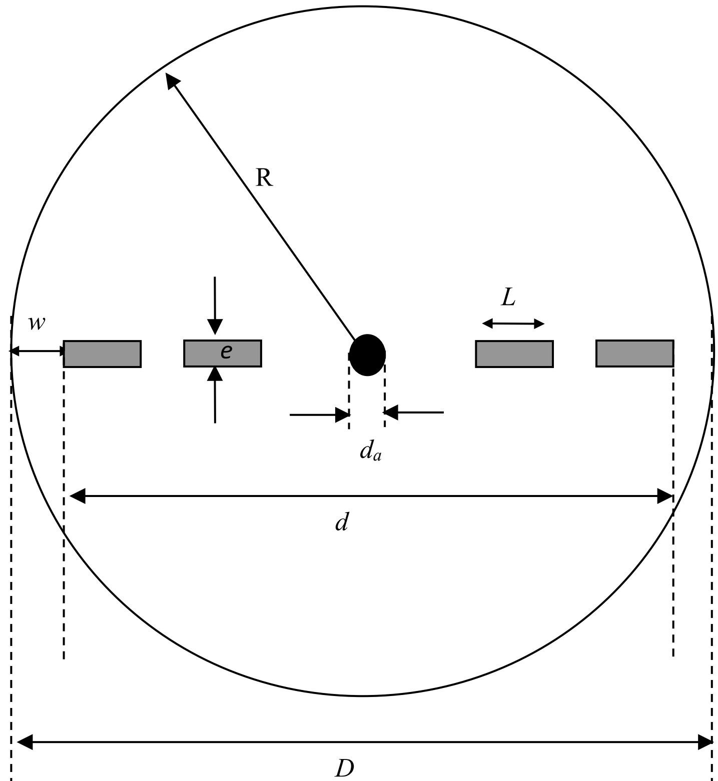

Figure 1: Computation domain.

2.1. Governing equation

The equations governing the flow are represented by equations which express the conservation of the mass, and the momentum equation respectively expressed in velocity-pressure-stress formulation which is necessary to add a behavior law for the fluid to close the system.

- Continuity

$$\rho \frac{\partial V}{\partial t} + \nabla(\rho \vec{V}) = 0 \tag{8}$$

- Momentum

$$\rho\left[\frac{\partial \vec{V}}{\partial t} + \left(\vec{V}.\nabla\right)\vec{V}\right] = \vec{f} - \nabla P + \nabla.\tau = 0 \tag{9}$$

Introducing the second invariant of the stress tensor, Equation 6 becomes:

$$\rho\frac{\partial\vec{V}}{\partial t}+\left(\vec{V}.\nabla\right)\vec{V}-\eta(\dot{\gamma})\Delta V-2D_{ij}\cdot\nabla\eta(\dot{\gamma})+\nabla P=0 \tag{10}$$

Three dimensionless numbers governing the flow are then:
Reynolds number characterizes the inertia.

$$\mathrm{Re}=\frac{\rho ND^2}{\eta_\infty} \tag{11}$$

Bingham number characterizes the yield stress of flow.

$$Bi=\frac{\tau_0}{\eta_\infty.N} \tag{12}$$

Hedström number characterizes the cross effect between inertia and viscoplasticity.

$$He=\mathrm{Re}.Bi \tag{13}$$

2.2. Boundary conditions

In the used CFD code, two reference frames can be treated. One is stationary, the impeller is in rotation and the tank is fixed. The other frame, which is rotating, the impeller is kept stationary while the outer wall of the vessel is given an angular velocity equal and opposite to the velocity of the rotating frame. Constant boundary conditions have been set respecting a fixed reference frame (RRF) approach.

The boundary conditions for velocity are fixed on the impeller and the vessel.

- On the impeller: Moving reference frame implemented in the CFD code.
- On the vessel: Wall moving with rotational speed equal zero.

2.3. Numerical simulation

Computational fluid dynamics (CFD) is playing a key role in helping to understand the flow inside stirred tanks. It is becoming a useful tool in the analysis of the highly complex flow inside stirred vessels [18].

The 2D flow field generated by a gate impeller in the agitation of yield stress fluid was simulated using the commercial CFD package (Fluent V6.3). The conservation of mass and momentum equations in the laminar regime were solved using the finite volume method. The first step in this method is to divide the calculation domain into discrete control volumes. This step is also referred to as grid generation. A pre processor (Gambit 2.0, Fluent Inc.) was used to discretize the flow domain with a tetrahedral mesh. In general, the density of cells in a computational grid needs to be fine enough to capture the flow details, but not so fine, since problems described by large numbers of cells require more time to be solved.

The bi-viscosity law is not pre definite in the package thus; we elaborate a user defined function which will be implemented. Convergence is assumed when the norm of the change in solution vector between successive iterations is less than 10−6.

3. RESULTS AND INTERPRETATIONS

3.1. Components of velocity

Before seeing the influence of the parameters mentioned before on hydrodynamics, the flow generated by plan impellers such as, a gate, have a tangential aspect, this result was validated in the works [19-20] this is why we are particularly interested in the tangential velocity.

3.1.1. Influence of inertia

The variation tangential velocity is given in Figure 2 and 3. The component tangential velocity in the impeller plan varies as follows: increases from the centre to the first blade, a linear increase between the two extremities of the first blade, then a decrease until a relative minimum, then an increase until the internal end of the second blade. The same happens at the level of the second blade. At the end a sharp decline up till the wall velocity which is null. We also notice that tangential velocity increases with the increase of the Reynolds number in two zones, one between the axis of the agitator and the first blade and the other between the two blades of the agitator. On the median plan, tangential velocity is almost zero for weak Reynolds numbers. When the inertia increases the tangential velocity increases as well. This situation can be explained by the fact that inertia increases tangential velocity whether in the impeller plan or the median one.

3.1.2. Influence of yield stress

In order to analyze the influence of the yield of flow, we have studied the flow of four fluids of Bingham of constraint threshold $\tau 0$ equalizes 0, 1, 5 and 30 Pa. These values correspond to a dimensional Hedström numbers 0, 8294, 41472 and 248.832. He value equals to zero corresponds to the Newtonian case. Angular velocity has been fixed at 1 rpm. The results are represented on Figure 4 and 5. Inversely with the effects of inertia discussed in the previous paragraph, we observe that for the greatest values of Hedström number, tangential velocity on the two plans decreased considerably. We conclude that any change in the yield stress implies a change in the behavior of the fluid. That is, an increase in the yield stress means that the velocity is vanished in a large area of the vessel and the fluid has a solid behavior.

3.1.3. Cross effect between inertia and plasticity

Figure 6 represents the global fields of tangential velocity for the following Bingham numbers: 30,200,800 and 5500. It is noted that, the fields are identical. For the greatest value of Bingham corresponds to the existence of broad immobilized areas and thus to sheared zones reduced in the vicinity of each blade. In this type of flow, viscosity is very high in the major part of the field and thus a solid behavior of the fluid. When the Bingham number decreases, we can consider that the effects of inertia are any more negligible in front of the effects of yield and the fields do not evolve in an identical way. There is a simultaneous influence of the two effects when the effects of inertias override the effects of yield of flow (weak Bi); the fluid is sheared in almost the totality of the tank. Consequently the behavior becomes simply that of a Newtonian fluid.

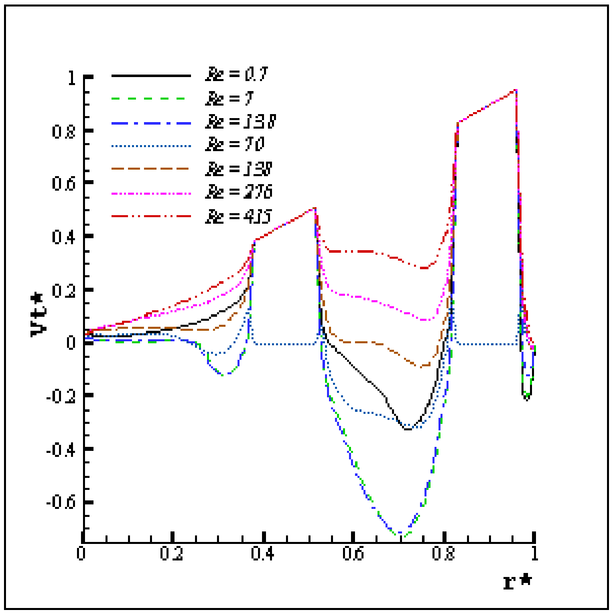

Figure 2: Tangential velocity on the impeller plane for different Reynolds numbers.

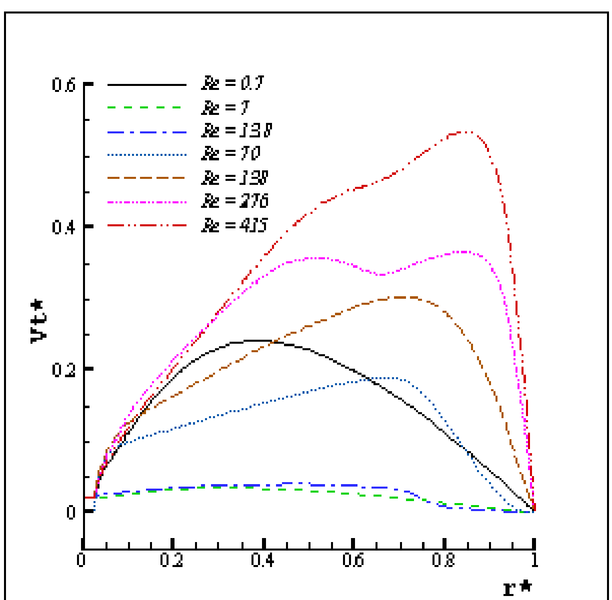

Figure 3: Tangential velocity on the median plane for different Reynolds numbers.

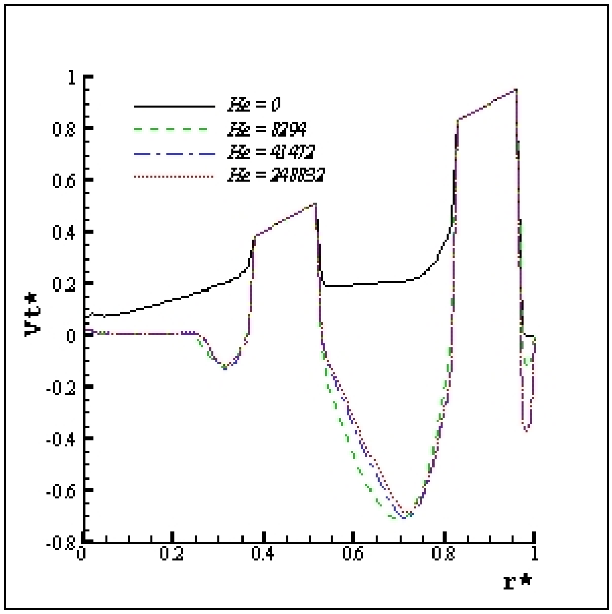

Figure 4: Tangential velocity on the impeller plane for different Hedström numbers.

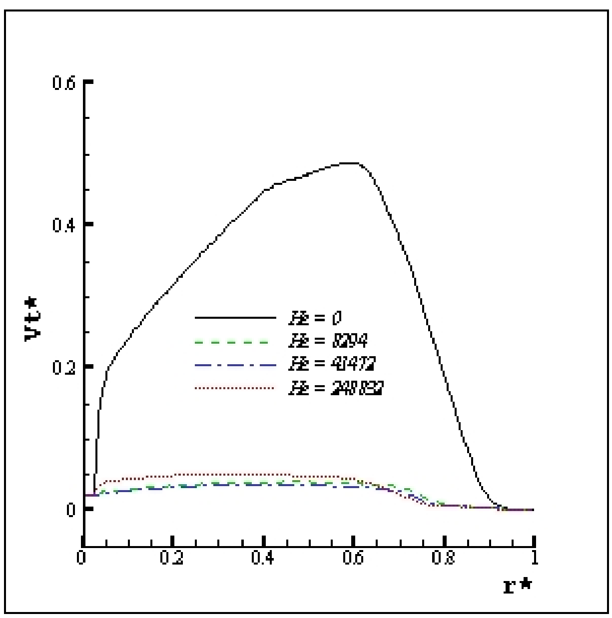

Figure 5: Tangential velocity on the median plane for different Hedström numbers.

3.2. Consumed power

The results obtained are presented on Figure 7 (N varying from 0.05 to 30 rpm). We notice that the power number varies linearly according to inertia; this is true for the weak Reynolds numbers. On the other hand, the product Np*Re is constant and equals to 472 beyond this value, one observes a fast increase in the Np*Re product, which thus means that the consumption increases more quickly than the Reynolds number does Figure 9.

Since we treat a non Newtonian fluid, the viscosity is not constant from where the need for introducing a new concept in term of generalized Reynolds noted Reg. We observe in particular very important values of Np for small Reynolds numbers Figure 7 and 8. In addition, a less consumption of power according to the generalized Reynolds number.

It is thus obvious that in Bingham fluid, the number of power Np as a function of the Reynolds number Re does not allow the interpretation of the effects of the yield stress. In contrast, we represent the Np*Re quantity as a function of Bingham number Figure 10, always for the whole of the treated cases, we observe a regular evolution of Np*Re which tends towards the Newtonian value Np when Bi tends towards zero. The number of Bingham thus integrates the two effects, of course, on this global quantity which is the power number.

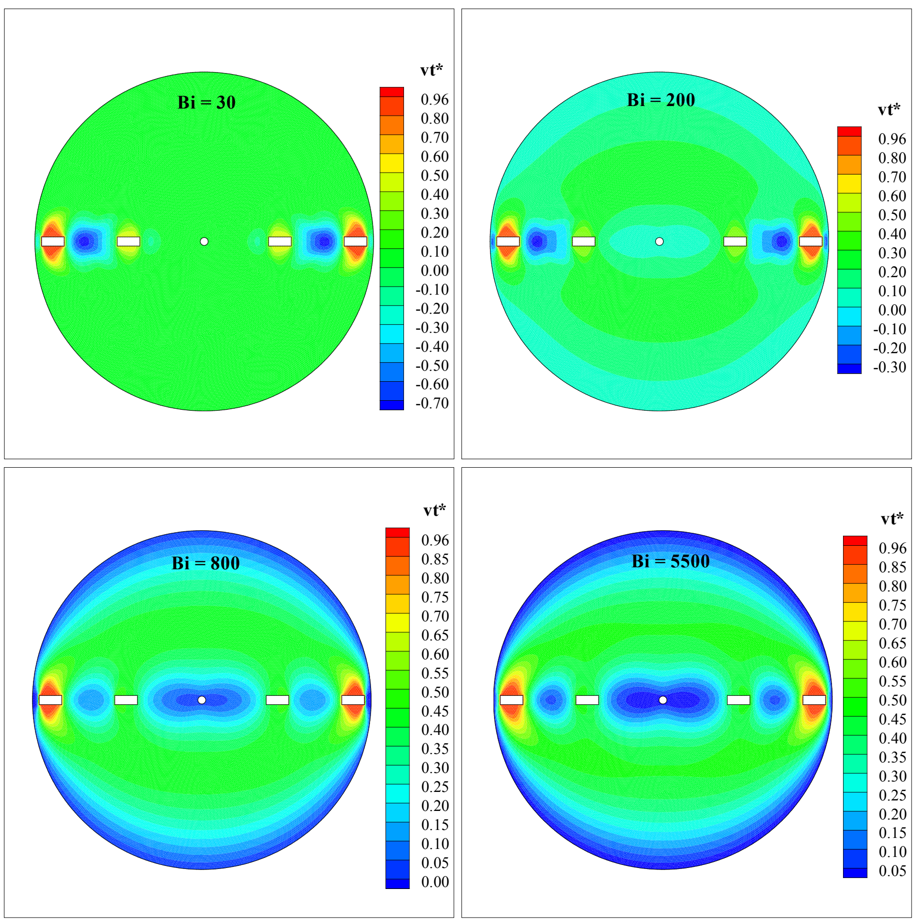

Figure 6: Tangential velocity for different Bingham numbers.

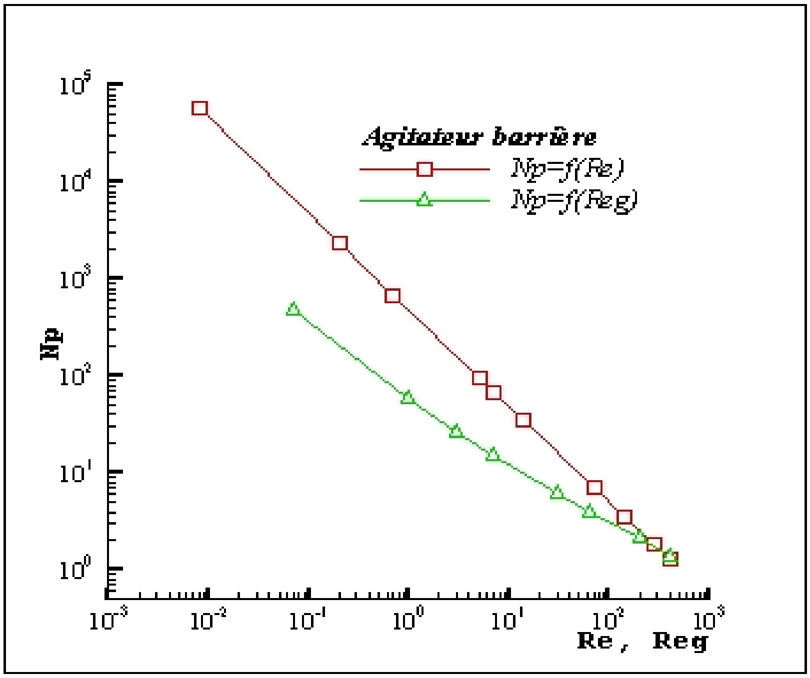

Figure 7: Variation of the power number as a function of Reynolds and generalized Reynolds numbers.

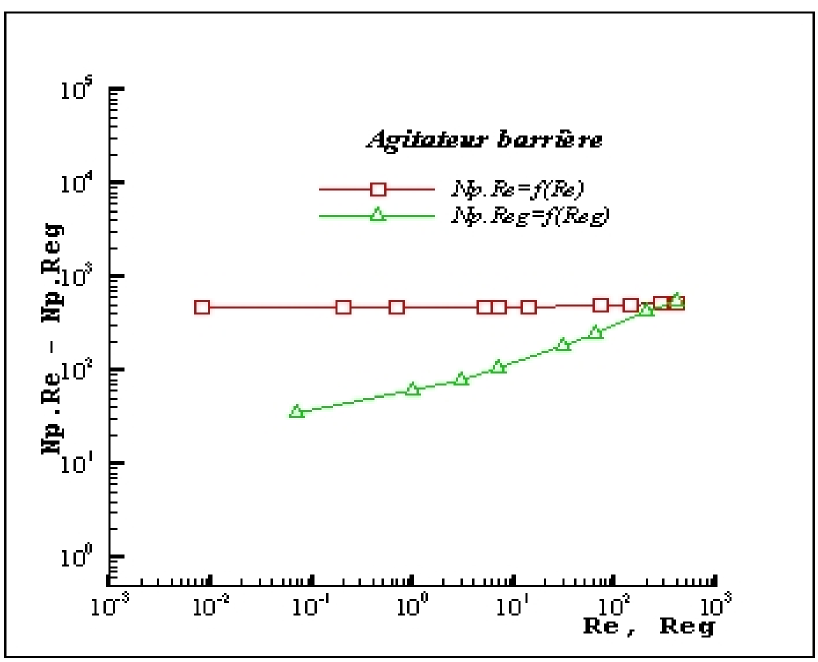

Figure 8: Variation of the product Np*Re and Np*Reg as a function of Reynolds and generalized Reynolds numbers.

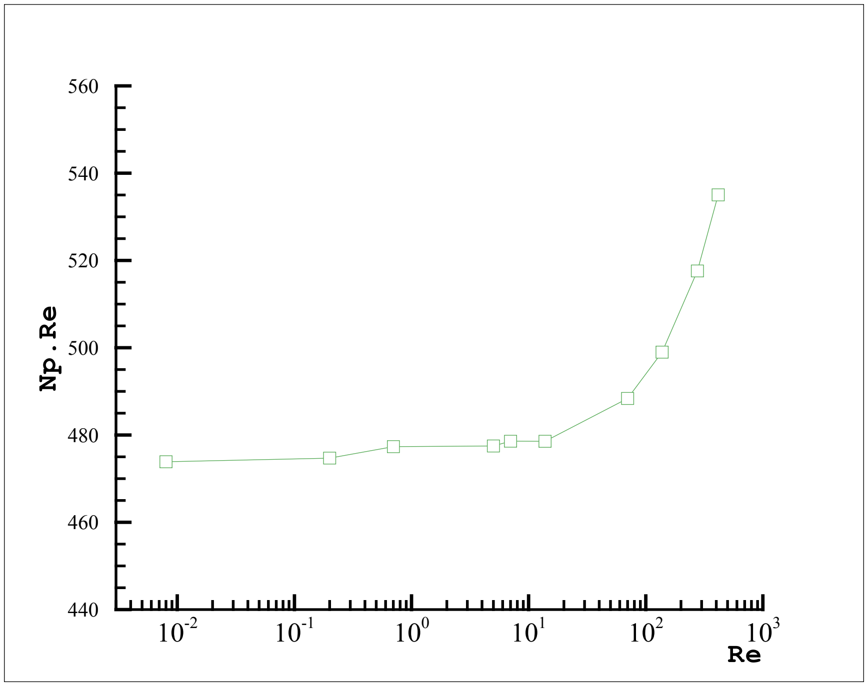

Figure 9: Variation of the product Np*Re as a function of Reynolds number.

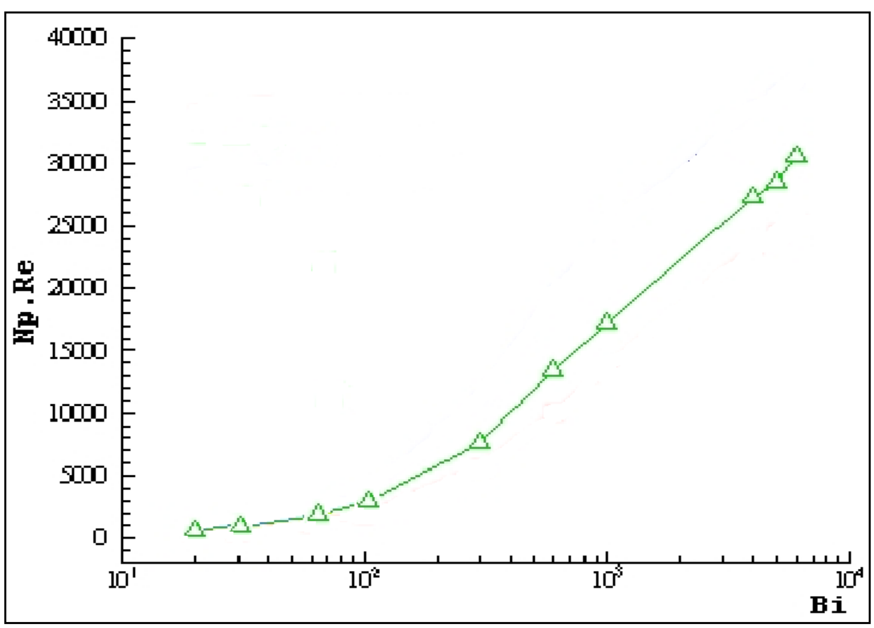

Figure 10: Variation of the product Np*Re as a function of Bingham number.

4. CONCLUSION

This contribution focuses on the viscoplastic fluids, which behavior is poorly controlled and which intervene in many processes, particularly the polymerization in emulsion. During the latter, the behavior progresses through time: practically, Newtonian at the beginning of the reaction, then becomes shear thinning and finally viscoplastic as long as the concentrations increase. The hydrodynamics of viscoplastic fluids in complex geometries such as the systems of agitation is modestly approached. However it plays a significant role, in the control and the effectiveness of processing since it conditions the heat and mass transfer. The problem is analyzed under the numerical aspect. The latter is not treated by a specific code but using an existing industrial code which is the fluent code. The numerical simulations carried out in geometries 2D made it possible to show the important significations by the viscoplastic behavior and in particular, the quasi immobilization of the fluids in a broad area when the effects of yield are dominant. It is worth nothing that this figure does not work if we consider the mixture of two substances of this type of fluid.

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