Ascanio, Gabriel; Foucault, Stepáne; Heniche, Mourad; Rivera, Christian; Tanguy, Philippe A.
Chaotic mixing in stirred vessels: A new strategy to enhance homogeneity
Ingeniería Mecánica, Tecnología y Desarrollo, vol. 1, núm. 6, marzo, 2005, pp. 209-214
Sociedad Mexicana de Ingeniería Mecánica
Distrito Federal, México

Available in: http://www.redalyc.org/articulo.oa?id=76810603
Chaotic mixing in stirred vessels: A new strategy to enhance homogeneity

Gabriel Ascanio¹, Stepháne Foucault², Mourad Heniche², Christian Rivera² and Philippe A. Tanguy²

¹ CCADET-Universidad Nacional Autónoma de México, PO Box 70-186, Mexico City, Mexico 04510
² URPEI-Ecole Polytechnique PO Box 6079, Stn. CV, Montreal, Canada H3C 3A7
E-mail: ascanio@aleph.cinstrum.unam.mx, stephane.foucault@polymtl.ca, mourad.heniche@polymtl.ca, christian-alberto.rivera-aparicio@polymtl.ca, philippe.tanguy@polymtl.ca

ABSTRACT

The mixing of inelastic Newtonian fluids was experimentally and numerically investigated by using eccentric impellers in stirred tanks. Two different scenarios based on single and dual off-centered impellers were proposed and compared to the standard steady-stirring configuration. Mixing times were experimentally measured by means of a color-discoloration technique based on a fast acid-base reaction, which allowed also revealing the formation of well-mixed zones (pseudocaverns) as well as segregated regions. The finite element method (FEM) was used for modeling the mixing tank with the centered impeller, while a virtual finite element method (VFEM) with unstructured grids was used for the modeling the laminar flow when eccentric impellers are used. The latter method allowed modeling the flow reducing considerably the processing time compared to the traditional simulation method (finite element method). Results obtained from this work show that if the operating conditions are properly set, mixing times can be drastically reduced compared to those obtained under the standard configuration (centered impeller under steady-state conditions), especially for high viscosity fluids.

Keywords: chaotic mixing, dynamic perturbations, asymmetry conditions, pseudocaverns, segregated regions

INTRODUCTION

Mixing is encountered widely throughout in many industrial processes involving physical and chemical changes. Some examples of industries requiring mixing in their processes are food, chemical, paper and waste treatment among others. At low Reynolds numbers, pseudocaverns, defined as well-mixed isolated regions can be formed close to the impeller. As a consequence either long or infinite mixing times are required. In other cases, two ring vortices can be formed below and above the impeller (Solomon et al, 1981). These regions can be avoided if the impeller speed is increased. However, higher energy consumption is required and the operating costs can drastically increase. On the other hand, increasing the rotational speed of the impeller can solve these problems, however, the fluid is submitted to high-shear rates, which can be a drawback for shear-sensitive media. It has been demonstrated that mixing can be clearly enhanced if the flow is continuously perturbed.

Aref (1984) demonstrated in a theoretical study that mixing could be improved if the flow is continuously perturbed, preventing the formation of coherent segregated regions in the vicinity of the impeller. These results were later confirmed by Ottino (1990), Swanson and Ottino (1991) and Muzzio et al (1991, 1992) with eccentric cylinders rotating in both directions during short times. Lamberto et al (1999) reported, in a numerical study, the existence of two ring vortices above and below the impeller, whose size and position is highly dependent on the Reynolds number. Another way for improving mixing in stirred vessels consists of using off-centered impellers (Alvarez, 2000; Alvarez et al, 2002) or by combining dynamic flow perturbations and impeller offsetting (Ascanio et al, 2002).

Published studies dealing with flow numerical simulations using Computational Fluid Dynamics (CFD), have been mainly focused on the hydrodynamics of steady-stirring vessels, and only a few investigations have been performed on the hydrodynamic complexities generated by the rotating impeller. The flow simulation of eccentric impellers poses special numerical challenges. Since no symmetry conditions are used, the unsteady version of equations of motion must be solved and a new computational mesh is a priori required at every time step, which is a major hurdle in terms of the computational costs. This problem has been successfully solved using an approach called the virtual finite element method (VFEM), which was introduced by Bertrand et al. (1997). The method was specifically developed for the analysis of flow problems involving moving parts such as impellers in an...
agitated vessel. Recently, Rivera et al. (2004) reported the successful use of this method for modeling the flow generated by centered and eccentric mixer configurations.

The objective of the present work is to compare experimentally and numerically the performance of mixing of inelastic Newtonian fluids with two different scenarios based on asymmetric geometry conditions and time-dependent perturbations and the use of two off-centered impellers. The results obtained with the proposed configurations will be compared with those obtained with the non-baffled steady stirring configuration.

MATERIALS AND METHODS

Experimental

Aqueous solutions of corn syrup were used as working fluids having a viscosity range from 0.15 Pa s to 0.5 Pa s. After preparing the solutions, they were allowed to settle during 24 hours before starting the experiments in order to eliminate air bubbles. Mixing times were evaluated by means of a color-discoloration technique based on a fast acid-base indicator reaction as proposed by Lamberto et al (1996). The tracer solution was prepared with water and purple bromocresol as indicator. Mixing times were measured for base → acid and acid → base reaction schemes. For subsequent mixing experiments, the amounts of NaOH and HCl were increased slightly to ensure operating in thoroughly acidic or basic media. Even though, small amounts of HCl or NaOH were added to the tank, fresh solution was used after eight experiments in order to avoid significant viscosity changes. The mixing experiments were performed at room temperature (~ 23 °C).

Figure 1 shows the mixer configurations considered in this work. The mixing system used for scenario 1 (non-symmetric geometry conditions with time-wise dependent perturbations) consists of a transparent vessel of 165 mm inner diameter and 210 mm height (see figure 1a). The tank can be horizontally displaced to adjust the degree of radial offset position of the impeller. A radial flow impeller (Rushton turbine) was fitted to the mixing shaft, which was driven by an AC motor that can be moved vertically to adjust the impeller clearance from the vessel bottom. A solid-state frequency changer receiving a feedback signal from a speed encoder carefully controlled the motor speed.

The mixing system built for scenario 2 (two off-centered impellers) consists of an open top transparent vessel of 215 mm inner diameter and 300 mm height and two Rushton turbines. Each turbine was driven by its own shaft actuated by a DC motor (0.186 kW) and a DC controller. One shaft was fixed with respect to the vessel whereas the second shaft could be horizontally or vertically moved by means of a counter-weight mechanism. The experimental flow patterns were obtained by means of color video camera and a digital camera, which were set on tripods keeping a constant distance from the tank.

Figure 1. Mixing scenarios (dimensions in mm): (a) Scenario 1, (b) Scenario 2.
Numerical simulation

Mixing flow simulations were carried out based on the virtual finite element method by solving the equations of motion. Briefly, the method consists of representing the rotating impeller by a series of control points located on the surface and to enforce the kinematics of these control points by constraints. The centered impeller configuration was modeled in the Lagrangian frame of reference while the Eulerian formulation was adopted for the eccentric configuration. The virtual finite element method is a modified Galerkin finite element method that lies within the framework of the fictitious domain method. It uses two computational meshes: (1) a volume mesh for the vessel; (2) a surface mesh of the impeller and the shaft where the control points are located. In the present work, the vessel was meshed with $P^+_1 - P_0$ piecewise enriched linear velocity and constant pressure tetrahedral finite elements (Bertrand et al. 1992) that offer all the guarantees of numerical stability and convergence.

I-DEAS (EDS) software was used to generate the geometry of the tank and the impeller, the tank volume mesh and the impeller-shaft surface mesh. The same software was also used to model the moving part. POLY3D (Rheosoft Inc.) was used as 3-D finite element numerical engine for the flow simulations. Results were graphically post-processed by means of ENSIGHT (CEI). A detailed description of the method can be found in Rivera et al. (2004).

RESULTS

Experimental

Mixing times under the conventional configuration (steady-stirring) are shown in Table 1. It is observed that the fluid homogenization into the tank is quickly achieved when low-viscosity fluids are used. This can be noticed in runs a1 and a2 with the impeller rotating at 100 RPM and 400 RPM, respectively. In the case of high-viscosity fluids, a long mixing time is required at a speed of 400 RPM (see run a4). Due to the formation of pseudocaverns from the very beginning of the experiment, the segregated regions remained visible after several mixing hours. As a consequence, no homogenization was achieved and the mixing time was considered as infinite (see run a3). Such a case is illustrated in Figure 2.

Tables 2 and 3 show the mixing times with scenarios 1 and 2, respectively.

The radial and axial positions play a fundamental role on mixing when using an off-centered impeller rotating in both directions. As Table 2 shows, the use of scenario 1 gives better results for high-viscosity fluids. An example of this fact is presented in run b16, in which a mixing time 28 times shorter is obtained compared to that obtained under steady-stirring conditions. Figure 3 shows a sequence of run b16; it is observed how segregated regions formed in the beginning are readily destroyed and the fluid is quickly homogenized. However, no enhancement is observed for the same fluid with the impeller rotating in both directions at low speed (runs b1, b6 and b7). In other cases, mixing time increases when using this scenario.

Table 1. Mixing times for the conventional configuration.

<table>
<thead>
<tr>
<th>Run</th>
<th>Variables</th>
<th>Mixing time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$x^*$</td>
<td>$y^*$</td>
</tr>
<tr>
<td>a1</td>
<td>0</td>
<td>1/3 $H$</td>
</tr>
<tr>
<td>a2</td>
<td>0</td>
<td>1/3 $H$</td>
</tr>
<tr>
<td>a3</td>
<td>0</td>
<td>1/3 $H$</td>
</tr>
<tr>
<td>a4</td>
<td>0</td>
<td>1/3 $H$</td>
</tr>
</tbody>
</table>

$x$ and $y$ are the radial and axial position of the impeller, respectively. Segregated regions remained visible even for several mixing hours and as consequence no homogenization was achieved.

Figure 2. Caverns formed 15s after starting from rest (run a3)
The use of scenario 2 gives in general terms better results for high-viscosity fluids. This can be observed when comparing run c6 with run a3. For the steady-stirring conditions no homogenization was achieved, therefore the mixing time was considered infinite. In the case of scenario 2, if the impeller B (see Fig. 1) is placed at the extreme position in the x direction (1/5 T) and it is slightly displaced in the vertical direction (1/3 H), a mixing time of 681 s is obtained. In such a case, both impellers rotated at 100 RPM. However, although the fluid is homogenized under similar conditions with the impeller B at the extreme axial position (2/3 H), the mixing time of run c7 is three times longer than the corresponding to run c6. Figure 4 shows a sequence using two Rushton turbines rotating at 100 RPM (run c7) at three different moments; it is observed that no segregated regions and the fluid is homogenized after 35 minutes.

**Numerical**

In order to assess the quality of VFEM solutions, a reference solution based on a standard FEM was generated. The computational mesh of the reference solution comprised 186 000 tetrahedral elements and 424 000 nodes yielding a linear system of $1.2 \times 10^8$ equations.

Figure 5 shows the computed velocity field of reference solution in the XZ plane. Two segregated regions represented by two tori, one above and one below the impeller is observed, which is in good agreement with the experimental observations of Lambert et al. (1999). It is important to point out that the color-discoloration technique used in this work allows determining the mixing times in stirred vessels and observing well-mixed isolated regions and segregated zones. However, it does not provide quantitative information to be compared with CFD results. For that reason, a possible comparison between the experimental and numerical results may be done from qualitative standpoint. The experimental flow pattern observed in Figure 2 was obtained 15 seconds after the impeller was turned on. This is the reason for which the torus formed below the impeller in the beginning does not appear in such a figure.

For scenario 2, the velocity field in XZ and XY planes with two Rushton turbines rotating at the same speed with a high viscosity fluid (run c7) is shown in Figure 6.

Although, both impellers rotate at the same speed, one can observe than impeller B has a stronger influence that impeller A on the flow field, and one can expect that the pseudocavities and segregated regions probably formed in the beginning will be quickly destroyed and as a consequence the fluid into the tank will be thoroughly homogenized. This effect was also observed by Ascanio et al. (2002) with radial flow impellers (Rushton turbines). The influence of impeller B is more evident looking at the XY plane (Fig. 6b), in which a region of high speed is formed between the impellers. Although, the

Overall, a positive effect on mixing time is observed when the Rushton turbine is axially displaced. Although, the impeller changes of rotation direction, the fluid will be always discharged in the same direction, therefore the pumping direction does not play an important role when using radial flow impellers (Rushton turbine).
Figure 3. Effect of asymmetric conditions and dynamic perturbations on mixing time of a high-viscosity fluid mixed with the Rushton turbine (run b16): (a) 65; (b) 16 s; and (d) 41 s.

Figure 4. Mixing sequence using two Rushton turbines rotating at 100 RPM: (a) 520 s; (b) 1044 s; and (c) 2050 s.

numerical determination of mixing times using this configuration could be expensive due to the long computing time, the flow patterns showed here, gives a good idea of the hydrodynamics into the stirred vessel with two off-centered impellers.

CONCLUSIONS

Two different unconventional configurations have been compared with a steady-stirring configuration for improving mixing times in stirred tanks using Newtonian fluids. It was demonstrated that segregated regions are readily destroyed by means of asymmetric geometry conditions combined with dynamic perturbations. With two off-centered impellers, no segregated regions were formed and better homogenization was achieved. A stronger influence of geometry conditions was observed on mixing times with this arrangement. On the other hand, both configurations were successfully modeled by the virtual finite element method. Overall, these scenarios have been proven to be efficient alternatives to conventional mixing, with better results obtained at higher viscosity.

Figure 5. Velocity field reference solution in XZ plane (velocity in m/s).
ACKNOWLEDGEMENTS

The financial support from NSERC for this research is highly appreciated.

REFERENCES


