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Design of multiple impeller stirred tanks for the mixing of highly viscous fluids using CFD

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Abstract

The effect of multiple Intermig impeller configuration on hydrodynamics and mixing performance in a stirred tank has been investigated using computational fluid dynamics. Connection between impeller stages and compartmentalisation has been assessed using Lagrangian particle tracking. The results show that by a rotating the Intermig impeller by 45° with respect to its neighbours, instead of a 90° rotation as recommended by manufacturers, enables a wider range of operating conditions, i.e., lower Reynolds number flows, can be handled. Furthermore by slightly decreasing the distance between the lower two impellers, fluid exchange between the impellers is ensured down to $Re = 27$.

Keywords: Mixing; Laminar flow; Hydrodynamics; Homogenisation; Computational fluid dynamics; Intermig impeller

1. Introduction

The mixing of highly viscous fluids is a common operation in the chemical, pharmaceutical, biochemical and food industries. Nevertheless, efficient mixing remains a difficult task, as does the design and scale-up of the stirred tank itself. Close clearance impellers such as screws, helical ribbons and anchors are well adapted to the processing of highly viscous liquids; however, they are less efficient when a change in viscosity occurs throughout the process. For such applications, coaxial stirring systems combining a close clearance agitator with a turbine or axial flow impeller, and also large diameter ratio axial agitators, e.g. Intermig or double-flux impellers, may be more appropriate (Letellier et al., 2002).

Intermig is an interference multistage counterflow impeller that has an inner pitched blade and an outer double blade arranged in a staggered position with an opposing blade angle. Due to the staggering of the outer blades, interference is produced causing a distinct axial deviation of the flow. As a result, these low-shear axial flow agitators used at large diameter ratios ($0.5T$–$0.95T$) are highly suitable for blending, suspending, dispersing, as well as heat transfer applications in both the laminar and transitional flow regimes. Typically, following manufacturers' instructions (EKATO, 1991), Intermigs are installed in pairs, each being rotated 90° respect to one another and are separated vertically by a distance of $0.5T$ to effectively mix at Reynolds numbers $(Re) > 100$.

Due to their versatility and effective performance for a number of applications in varying flow regimes, it is not surprising that Intermig impellers are readily used in the process industries. However, it appears that there have been very few studies published in the literature that concern the flow and performance of these agitators. Nienow (1990) found that when the inner blades of the Intermig pump downwards in gas-dispersion applications, flooding occurs much more easily than when they are up-pumping. Ibrahim and Nienow (1995) used streak photography to examine the flow patterns produced by a pair of Intermigs and concluded that the flow patterns produced are complex and very different from the schematic diagram given by the manufacturers. They also compared the power curves of the impellers with down-pumping and up-pumping inner blades for laminar through to turbulent flow regimes. The curves coincided for the entire range of Re and for three values of impeller clearance. More recently, Szalai et al. (2004) have analysed the mixing performance of four Intermig impellers (separated

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by $0.58T$) for $Re = 37$, 50, 100 with experimental and numerical techniques. Using particle image velocimetry (PIV) and plane laser-induced fluorescence (PLIF), as well as Computational Fluid Dynamics (CFD), it is shown that the flow pattern produced by the Intermig impellers is complex and highly three-dimensional. The authors found that for low Re, severe compartementalisation occurs, preventing mixing in the axial direction. It is shown that by varying the agitation rate at periodic intervals, the vertical segregation is broken and mixing at low Re is improved. This technique had been previously employed for improving the mixing performance in a typical tank configuration stirred with a disc turbine (Yao et al., 1998).

As discussed by Szalai et al. (2004), one of the most challenging tasks in the process industries is the design and scale-up of reactors for processing of highly viscous fluids. Experimental studies are often restricted to the acquisition of global values, e.g., mixing times, due to the fact that there are not a lot of experimental techniques that allow the measurement of local velocities in high viscosity fluids. The classical techniques, such as laser Doppler velocimetry and PIV, which enable local measurements, are often limited for use in high-viscosity liquids due to the diffusion of the laser beam or sheet. CFD, on the other hand, is not limited by such technological aspects. It can be used as a sort of 'numerical probe' or sensor to obtain local information about the complex flow field and is therefore an extremely valuable and reliable tool for laminar process design. Nevertheless, efficient methods for characterising complex three-dimensional laminar flow fields are still required. Typically, the results of CFD calculations are presented as two-dimensional velocity vector fields; these however can give completely misleading impressions about the flow. Much work has been done by Muzzio and co-workers concerning the characterisation of complex laminar flow fields (see for example Lamberto et al., 1999 or Szalai et al., 2004). They quantify mixing efficiency by calculating the stretching intensity of a particle trajectory as a function of position and time. Although their method gives much insight on the complex nature of laminar flows, the computational effort is rather important. With this in mind Harvey III et al. (2000) set out to develop a particle-mapping technique to quantify laminar mixing performance in a multiple impeller stirred tank. Their method has enabled the calculation of a 'mixing time', which is the time needed for a particle to travel a prescribed distance.

In this study, we focus on the performance of a tank stirred by four Intermig impellers, in terms of hydrodynamics, for viscous fluid processes using CFD. The aim is to determine the operating limitations of a typical configuration of the agitation system, and then to modify the configuration of mixing system so that a wider range of operating conditions can be handled. In order to evaluate the performance of the agitation system, particle trajectories have been calculated and a simple quantitative statistical analysis of the results has been carried out.

2. Tank geometry

The tank geometry employed in the work is a flat-bottomed cylindrical tank with a diameter (T) set to 1 m and the height to diameter ratio (H/T) of 2 (Fig. 1). The vessel is equipped with four Intermig impellers, diameter $(D) = 0.9T$, which are separated by a distance of $0.45T$. The off-bottom clearance of the lowest impeller is $0.22T$ (distance from the vessel bottom to the lowest impeller swept plane). Three different impeller configurations have been studied. The first case corresponds to a typical installation whereby the Intermig impellers are rotated by 90° with respect to one another. For the second and third configurations, each Intermig is rotated 45° relative to its neighbours in a clockwise and an anti-clockwise direction, respectively. The impeller rotates at 37 rpm such that the inner blade of the Intermig is down-pumping and the outer fork is up-pumping. Two other modified configurations, whereby the inner blade pumps upwards or the distance between the two lowest impellers is reduced, are then tested. The characteristics of each case are summarized in Table 1.

The model fluid used is Newtonian and has a density of $1100\,kg\,m^{-3}$. Three values of viscosity—equal to 9, 15, and 20 Pa s–have been tested, which correspond to Reynolds numbers of 60, 37 and 27, respectively.

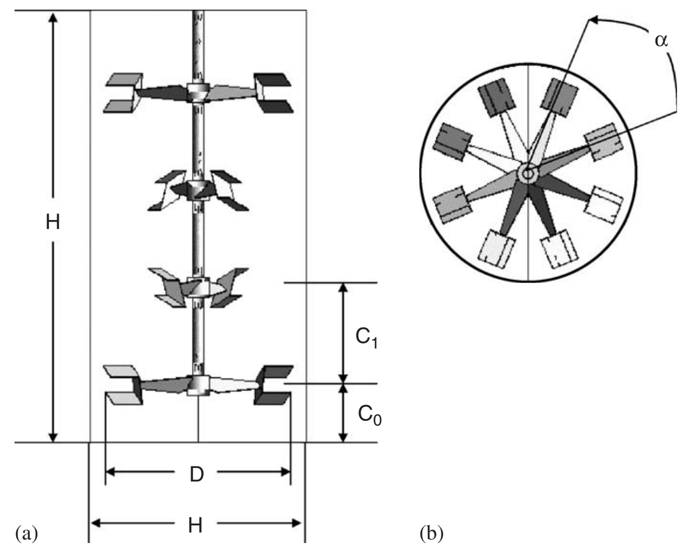

Fig. 1. Geometry of the vessel equipped with four Intermig impellers. (a) Side view with dimensions, (b) overhead view indicating the relative impeller rotation, α.

Table 1
Summary of the geometrical configurations studied

Case name	Relative impeller rotation, α	Pumping direction of inner blades	Distance separating impellers, C_1
IMIG-90	90°	Down	$0.45T$
IMIG-45CW	45° clockwise	Down	$0.45T$
IMIG-45ACW	45° anti-clockwise	Down	$0.45T$
IMIG-90-U	90°	Up	$0.45T$
IMIG-45ACW-C	45° anti-clockwise	Down	$0.4T$ for two lowest Intermigs $0.45T$ for others