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Prediction of fluid dynamic instabilities of low liquid height-to-tank diameter ratio stirred tanks

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HIGHLIGHTS

- Stirred tanks of unconventional geometry are widely adopted and poorly investigated.
- The relationship between flow field transition and free surface oscillation is found.
- The instability frequencies are identified by the FFT of the pressure time series.
- A novel interpretation of the instabilities' origin is proposed.

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ABSTRACT

In this work, original experimental data on the fluid flow instabilities associated with the oscillation of the liquid free surface in low liquid height-to-tank diameter ratio stirred tanks are presented. The local flow features of this type of tanks, which are commonly adopted as (bio)-reactors in important industrial productions such as drugs and bio-energy, are investigated by Particle Image Velocimetry. The local mean flow field and the turbulent characteristics are found to depend critically on the periodic variations of the liquid free surface, whose features vary as a function of the fill ratio. The frequency analysis of the dynamic pressure time series collected by a Pitot system shows that the frequency of the flow instabilities is mainly affected by the geometrical characteristics of the system. Therefore, the observed instabilities do not arise from the same origin of the so-called macro-instabilities previously identified in stirred vessels. A novel interpretation based on the liquid sloshing dynamics in cylindrical vessel is suggested.

1. Introduction

Mixing is a crucial unit operation in the chemical, biochemical and allied industries. It is often performed in mechanically stirred tanks, due to their ease of construction, cleanness and versatility of operation. A wide variety of stirred tanks' design are adopted in the industrial practice, depending on the process main requirements: blending of miscible liquids, dispersion of bubbles or droplets into a liquid phase, solids suspension, chemical or biological reactions, just to mention a few examples. In any case, it is well known that the performances of the mixing equipment are strongly dependent on the three-dimensional flow generated by the stirrer, as it affects the dispersed phase distribution, heat and mass transfer as well as the chemical reactions involved in the operation [1].

Thorough experimental and computational investigations have been carried out in the past 50 years on fluid mixing, leading to a deep knowledge of the flow and the mixing dynamics taking place in baffled stirred tanks of standard geometrical features [2] (tank height-to-tank diameter ratio, $H/T \geqslant 1$, and impeller diameter to tank diameter ratio, $1/3 \leqslant D/T \leqslant 1/2$). Attention has been also devoted to unbaffled stirred tanks of standard geometry, which are often adopted in pharmaceutical and food processes [3,4], in bioreactions with shear sensitive cells [5], for very viscous fluids [6] for carrying out fast chemical reactions [7]. As a difference with baffled tanks, the prevailing fluid flow of unbaffled cylindrical vessels is tangential and, depending on impeller speed and liquid height, a central vortex may expand from the free surface, whose depth has to be carefully monitored in order to avoid impeller flooding and gas entrainment. Vortex formation can be avoided when the vessel is completely filled and closed with a lid [8], but this configuration is not generally viable, such as for the anaerobic digesters, where a free space for the biogas accumulation over the top is required. The local flow field characterization inside

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unbaffled tanks has revealed that axial impellers tend to lose most of their typical pumping action, and that the majority of the kinetic energy of the fluid is consumed along the tangential direction [8,9].

Low tank height-to-tank diameter ratios and/or low liquid height-to-tank diameter ratios for vessels either provided or not provided with baffles are also adopted for important industrial operations in the pharmaceutical industries [10] and in anaerobic bio-processes [11]. The available knowledge gained so far on the fluid flow and the mixing dynamics encountered in reactors of this type is quite narrow. Further investigations would help improving design rules and operating conditions, since general predictive equations obtained in standard tanks cannot be applied even to calculate basic parameters, such as power consumption, flow number and mixing time, being the hydrodynamics produced by the impellers–tank interactions completely different. The gap of information is worth to be filled, due to the industrial interest on these configurations and the evidence gained in previous investigations of their quite complex fluid dynamic behavior [11], including the significant oscillations of the liquid free surface and the instabilities of the flow, whose quantitative characterization has never been reported so far.

In the detailed investigations of the fluid dynamic behavior of stirred tanks, temporal mean flow variations called macro-instabilities (MIs) have been observed for specific ranges of conditions and/or locations. The MIs, whose frequency is much lower than the impeller blade passing frequency, can strongly affect the mean velocity and r.m.s. velocity fluctuations [12], the mixing performances [13], mass and heat transport, the mixing times [14] and the liquid surface shape [15]. MIs were found to occur in stirred tanks from different origins: (a) the change of flow patterns due to the impeller clearance [16,17]; (b) the flow regime transition induced by a change of the Reynolds number [18]; (c) the occurrence of precessional vortices around the vessel axis [12,19]; (d) the instability of the impeller jet [20]. The instabilities of the mean flow have been investigated for stirred vessels of standard geometrical proportions provided or not provided with baffles and with a fill ratio equal or close to one. Different mechanisms and characteristic instabilities may be expected depending on the geometry, as shown among others by Galletti et al. [21] in the case of unbaffled stirred tanks of different shaft eccentricities. To the best of our knowledge, the flow instabilities in partially filled stirred tanks with low height-to-tank diameter ratio have never been investigated systematically, either by experimental or numerical techniques. The liquid free surface oscillations in a low height-to-tank diameter ratio model digester have been just visually observed [11], while the free surface shape and the relevant oscillation modes of liquid sloshing in containers have been widely investigated mainly by theoretical approaches [22,23]. Most of the results have been obtained solving the fluid flow equations under the hypothesis of potential flow (inviscid, incompressible and irrotational) and appropriate boundary conditions to account for the presence of lateral walls, thus determining the free surface flow and the resulting hydrodynamic pressure distribution, forces and moments. Besides, many experimental [24,25] and computational studies [26–28] have been carried out with the aim of determining the main features of liquid sloshing. Recently, the liquid sloshing dynamics encountered in orbital shaken cylinders has been investigated experimentally and interpreted by a potential sloshing model [29,30]. The conclusions drawn so far on the sloshing dynamics in moving or stationary containers of different shapes might be usefully related to the liquid free surface dynamics in the stirred vessels considered in this work.

With the specific purpose of identifying the relationship between the liquid free surface dynamics and the fluid flow characteristics of low liquid height-to-tank diameter ratio stirred tanks, detailed velocity measurements by Particle Image Velocimetry (PIV) and frequencies analysis of the dynamic pressure time series collected by a Pitot system are carried out. The liquid free surface influences greatly the entire system fluid dynamics and it may have a relevant impact on the performances of industrial apparatuses of similar geometry.

2. Materials and methods

The experiments were performed in two cylindrical stirred tanks of different dimensions, named T49 and T23 in the followings. The former has been investigated by both PIV and a Pitot system. For the latter, just selected measurements by the Pitot system have been collected, for specifically identifying the tank diameter effect on the flow frequencies by adopting the same impellers at the same clearances of T49. T49, that is shown in Fig. 1, consists of a low height-to-tank diameter ratio, flat-bottomed, unbaffled cylindrical vessel of diameter, T, equal to 0.49 m and height, H, equal to 0.255 m ($H/T = 0.52$). A cone of 0.025 cm height and 0.06 cm base diameter was placed centrally between the vessel bottom and the shaft lower end, as in the industrial digester of which the investigated T49 is a scale-down version [11]. T23 is a flat-bottomed unbaffled cylindrical vessel of diameter, T, equal to 0.232 m and height equal to 0.24 m ($H/T = 1.03$). In both cases, the mechanical agitation was provided by two identical Lightnin A310 impellers of diameter, D, equal to 0.098 m, the lower of which was placed at off-bottom clearance, C_1, equal to 0.039 m and at distance from the upper impeller, C_2, equal to 0.088 m. The impellers were mounted on a shaft coaxially with respect to the vessel axis and demineralized water was used as the working fluid. The shaft was mounted centrally on the vessel lid. The lid was fixed to the vessel by a flange placed on the vessel upper periphery, thus ensuring a very precise positioning and very limited wobbling of the shaft.

In T49, three different liquid heights, H_L (equal to 0.175 m, 0.2 m and 0.235 m, corresponding to 0.69H; 0.78H; 0.92H and to 0.36T; 0.41T; 0.48T, respectively) and fully turbulent rotational Reynolds numbers, Re (from 3.2×10^4 up to 9.6×10^4), were investigated in detail. The lower limit of the fill ratio was selected in order to avoid the flooding of the upper impeller, while the upper limit was close, but not equal, to the vessel height. Two fill ratios lower than one were also considered in T23 ($H_L = 0.71H$ and 0.83H).

Only for T49, the ensemble-averaged velocity field was determined by a standard 2D-PIV system in limited portions of a diametrical vertical plane of the vessel, named *zone A* and *zone B* in Fig. 1, in order to account for the strong variations of the flow moving from the impeller region toward the vessel wall. To minimize refraction effects at the curved surface, the vessel was placed inside a square trough filled with the working liquid. Polymeric seeding particles coated with Rhodamine B were used. The experimental system included a Litron Nd:YAG laser, emitting light at 532 nm with a maximum frequency of 15 Hz and energy equal to 65 mJ, and a HiSense MK II 1344 × 1024 pixels CCD camera, provided with an optical filter cutting off the light wavelength lower than that emitted by the fluorescent seeding particles. When the lower impeller discharge stream was investigated ('*zone A*'), the time interval between two laser pulses was experimentally set at $\Delta t = 850\ \mu s$ for the condition $N = 300$ rpm, and this value was then proportionally adjusted for all the other rotational speeds considered. Close to the vessel wall ('*zone B*'), minor variations of the flow and lower velocity magnitudes were detected, therefore a constant value of $\Delta t = 4000\ \mu s$ was chosen at any impeller speed investigated. The analysis of the instantaneous image pairs was carried out through the use of an adaptive-correlation algorithm, applied on interrogation areas (IA) of initial size 64 × 64 pixel ('*zone A*'), and 128 × 128 pixel ('*zone B*'). Two refinement steps together with