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Rotary sloshing induced by impeller action in unbaffled stirred vessels

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HIGHLIGHTS

- Free surface sloshing in non-standard unbaffled stirred vessels was measured.
- Different liquid viscosities, impellers and rotational speeds were investigated.
- Different sloshing modes are observed, depending on operating conditions.
- Oscillation frequencies depend on liquid viscosity, impeller type and speed.
- A model to predict the onset of sloshing and the relevant frequencies was developed.

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ABSTRACT

Unbaffled stirred tanks are characterized by a highly swirling fluid motion and, unless they are completely filled and closed with a lid, a central whirlpool takes place, whose depth depends on the impeller rotational speed. In some cases, periodic rotating waves appear, regardless of the axial symmetry of the system. These waves may result into undesirable periodic stresses for the structure, the vessel and the process connections.

In this paper, a comprehensive experimental study on the onset and the characterization of periodic free-surface oscillations in unbaffled stirred vessels is carried out. Different wave shapes (or oscillation modes) may be observed, depending on the operating conditions. The oscillation mode of the free liquid surface is experimentally evaluated by both visual observation and measurements of the local dynamic pressure time traces. The oscillation frequency is identified from the time traces by means of simple Fast Fourier Transform.

The natural frequency of each oscillation mode is in excellent agreement with predictions obtained by the theory of sloshing in case of still liquids in cylinders, but the effect of impeller is here analyzed in detail.

Several experiments using different tank geometries, filling ratios and liquid viscosities were carried out. In all cases, the observed frequency was found to increase linearly with the impeller speed, with a slope that depends on the impeller geometry and on the oscillation mode under analysis. A simple predictive model is developed and validated by comparison with experimental data.

1. Introduction

The mixing operation is a fundamental part of the process industry, adopted in all cases where there is the need for blending substances, dispersing phases (to generate gas-liquid or liquid-liquid dispersion) or suspending particles into a fluid medium. This operation is often carried out in stirred vessels, because of their ease of construction and operation, and their versatility.

The number of possible geometric configurations of stirred vessels is extremely high and strongly dependent on the operation that is carried out: main components (impeller type, size and position; vessel geometry and relevant internals) may be chosen to achieve optimal conditions in terms of operating and installation costs. The optimal configuration depends on the complex flow field generated by the combined action of the impeller and the vessel walls and internals, and, clearly, on the operation that has to be carried out.

Several investigations were carried out in the past dealing with the fluid-dynamic characterization of baffled stirred tanks [1],

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Nomenclature

C	impeller clearance from vessel bottom [m]
D	impeller diameter [m]
d_{hy}	hydraulic diameter [m]
$f_{0,mn}$	natural sloshing frequency [s^{-1}]
g	acceleration due to gravity [m s^{-2}]
H	vessel height [m]
H_l	liquid level at rest [m]
h_{mn}	surface elevation for sloshing mode m_{mn} [m]
m_{mn}	sloshing mode [–]
N	impeller speed [s^{-1}]
Q_{imp}	flowrate generated by the impeller [m^3 s^{-1}]
r	radial coordinate [m]
S	effective cross sectional area [m^2]
T	vessel diameter [m]
u_c	effective fluid speed [m s^{-1}]
$u_θ$	tangential velocity [m s^{-1}]
α	dimensionless speed for tangential velocity calculation [–]
λ_{mn}	wavelength of sloshing wave for mode m_{mn} [m]
μ	fluid viscosity [Pa s]
ξ_c	dimensionless critical diameter [–]
ξ_{mn}	root of the first derivative of the Bessel's function of the first kind [–]
ρ	fluid density [kg m^{-3}]
σ	surface tension [N m^{-1}]
φ	angular coordinate [rad]
ψ	slope of the f vs N curve [–]
$N_q = Q_{imp} N^{-1} D^{-3}$	pumping number [–]
$Re = \rho N D^2 \mu^{-1}$	Reynolds number [–]
$Ro = Q_{imp}^2 g^{-1} d_{hy}^{-2} T^{-1}$	Rossby number [–]
$St = \rho u_c d_{hy}^2 \mu^{-1} H_l^{-1}$	Stokes number [–]
$\Gamma(x) = \int_0^\infty e^{-t}t^{x-1}dt$	Gamma function

leading to a thorough knowledge of their characteristics in several single- and multi-phase operations. Nevertheless, the unbaffled geometry is often adopted in pharmaceutical and food processes [2,3], for mixing systems with chemical reactions [4] or as crystallizers. Baffles may result into undesirable stagnant zones if viscous liquids are stirred [5], and in these cases they are usually not adopted. Unbaffled vessels were also shown to be a viable solution for the growth of shear sensitive cells [6]

However, the overall knowledge of unbaffled stirred vessels is still scarce with respect to baffled vessels, and often focused on standard geometry vessels. Unbaffled vessels with unconventional H/T ratios (used in full scale fermenters) were found to have complex fluid-dynamic behavior, regardless of the quite simple vessel geometry [7]. In some cases, the onset of rotating inertial waves was observed, resulting from the deformation of the free surface [8,9], a behavior akin to the sloshing of liquids in tanks.

The free surface shape and the relevant oscillation modes of liquid sloshing in containers have been widely investigated mainly by theoretical approaches [10–12], being of fundamental importance in transportation and aerospace engineering. 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.

The spontaneous onset of rotary sloshing was observed in partially filled cylindrical vessels caused by upward directed liquid jet. Self-induced sloshing was observed in case of an upward jet impinging to the free liquid surface [13] and also in case in which a solid structure was partially immersed in the liquid [14]. The swell formed at the impingement point of the upward jet and the free surface may start to oscillate, inducing a synchronous sloshing of the surrounding water. Under specific conditions, a rotary sloshing without substantial circulating flow was also observed. The sloshing frequencies were found to be predictable by harmonic solution of the Laplace equation (Eq. (1)).

$$f_{0,mn} = \frac{1}{2\pi}\sqrt{\left[\frac{g\xi_{mn}}{T/2}\right]\tanh\left(\frac{\xi_{mn}H_L}{T/2}\right)} \quad (1)$$

where g is the gravity constant, T the tank diameter and H_l the liquid height. The values ξ_{mn}, are the roots of the first derivative of the Bessel-function of the first kind (reported in Table 1). Sloshing modes are usually identified by the number of nodal diameters m and nodal circles n. Each oscillation mode, identified by the (m,n) values has its own dominant frequency (and relevant harmonics) and free surface shape.

Table 1
Roots ξ_{mn} for m = 0 – 3 and n = 1–3 of the first derivative of the Bessel-function of the first kind to be used in Eqs. (1) and (2).

ξ_{mn}	m = 0	m = 1	m = 2	m = 3
n = 1	3,8317	1,8412	3,0542	4,2012
n = 2	7,0156	5,3314	6,7061	8,0152
n = 3	10,1735	8,5363	9,9695	11,3459

Two different feedback loops are claimed to exist when self-induced sloshing phenomena are caused by an upward jet, the first linked to the unbalanced pressure distribution, the other linked to the subsequent deflection of the liquid jet [13]. The superimposition of these two mechanisms is at the basis of the complex phenomenon, as shown by means of numerical simulations [13].

The onset of rotary sloshing was also observed in a cylindrical vessel with two stratified fluids agitated by a bottom blown liquid jet [15]. Different behaviors were observed depending on the physical properties of the fluids and their levels. The self-induced rotary sloshing caused by upward round jets was studied experimentally and numerically [16,17], as the induced sloshing may be able to accelerate reactions in suitably designed reactors and enhance mixing, or to increase the efficiency of molten steel refining [17]. The harmonic solution of the Laplace equation (Eq. (1)) was found to predict with excellent agreement the sloshing frequency. The experimental and numerical results about jet oscillations were in agreement with the model proposed by Madarame et al. [13], while CFD results were in good agreement with experimental PIV data. The analysis of self-induced rotary sloshing was also studied in cylindrical vessels with off-center upward jet [18]. The authors showed that the oscillating frequency was quite similar to that obtained with centered jets, and that CFD models were able to catch the main characteristics of surface swell and flow field.

Inertial waves were also observed in a cylindrical vessel with a drain hole in the center of the bottom [19]. The authors report that under some circumstances (depending on the values of dimensionless draining hole diameter and tank diameter) a large inertial wave with a frequency close to that of the natural frequency of water in the same vessel is observed.

Other references to rotary sloshing can be found in Ibrahim [12], but in that case the rotary sloshing is induced by lateral