Chemical Engineering Journal 254 (2014) 210–219

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Mixing dynamics in uncovered unbaffled stirred tanks

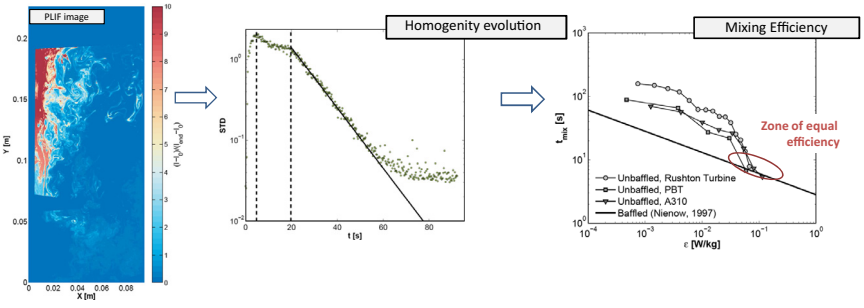
A. Busciglio *, F. Grisafi, F. Scargiali, A. Brucato

Dipartimento di Ingegneria Chimica, Gestionale, Informatica e Meccanica, Universitá degli Studi di Palermo, Viale delle Scienze, Ed. 6, 90128 Palermo, Italy

HIGHLIGHTS

- Mixing rates in uncovered unbaffled vessel are assessed by means of PLIF.
- Time evolution of spatial inhomogeneity was followed via PLIF maps standard deviation.
- Results show that two well-mixed, partially segregated regions exist.
- At near-critical conditions, mixing efficiency equals that of baffled tanks.
- A simple $D = T/3$ PBT impeller is found to be the best choice.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 25 February 2014
Received in revised form 16 May 2014
Accepted 19 May 2014
Available online 29 May 2014

Keywords:
Mixing
Stirred tanks
PLIF
Mixing time
Unbaffled

ABSTRACT

The present work is aimed at providing experimental information on mixing rates in an unbaffled vessel under free surface vortexing conditions. The planar laser induced fluorescence (PLIF) technique was used for measuring the dispersion dynamics of a passive tracer over a vertical section of the vessel. In agreement with the quite scant literature information available for these systems, results confirm the existence of two well defined, partially segregated, zones that give rise to a double mixing dynamics behavior.

A suitable mixing time definition is proposed and applied to a number of experimental runs with different stirrer geometries and agitation speeds.

Results confirm that unbaffled vessels are indeed poorer mixers than baffled tanks. In fact, when compared on the basis of same power input, *i.e.* in terms of mixing efficiency, mixing times are found to be 2–3 times larger than those pertaining to baffled tanks. However, in the 0.19 m diameter vessel employed, the observed mixing times typically fell in the range between 10 and 100 s, which makes them fully compatible with many applications involving relatively slow processes. Moreover, when free-surface vortex bottom approached the impeller plane, mixing efficiencies became practically identical to those of baffled tanks. This is a remarkable finding, as it considerably widens the potential application field of unbaffled vessels.

1. Introduction

Unbaffled stirred tanks are gaining a growing industrial interest as they provide significant advantages in selected applications, including a number of biochemical, food and pharmaceutical processes. As an example, their use may be recommended for bioreactors in which shear sensitive cells are grown (such as mammalian cells). As a matter of fact, unbaffled stirred tanks have been found to guarantee sufficient oxygen intake for cells growth, even in the absence of gas dispersion in the liquid phase [1,2], hence avoiding cell damage due to bubble bursting. Unbaffled mixers may also be conveniently used as crystallizers (especially for those in which fragile particles are generated). In general, either with [3] or without [4] top cover, they have been found to be very effective for any application involving particle suspension, such as ex-situ soil remediation.

* Corresponding author. Tel.: +39 091 238 63779.
E-mail addresses: antonio.busciglio@unipa.it (A. Busciglio), franco.grisafi@unipa.it (F. Grisafi), francesca.scargiali@unipa.it (F. Scargiali), alberto.brucato@unipa.it (A. Brucato).

http://dx.doi.org/10.1016/j.cej.2014.05.084
1385-8947/

However, there still is a general lack of information on their mixing performance, that needs to be addressed in order to better assess their application potential.

Mixing time (t_{mix}) is the main parameter commonly employed to assess the mixing performance of single phase stirred tanks. It is defined as the time required to achieve a given level of homogeneity in an initially non-homogeneous mixture.

Several mixing time measuring techniques, comprehensively reviewed by Patwardan and Joshi [5], have been proposed over the years. In practice, the experimental techniques employed can be generally classified in two groups: (i) *observation* and (ii) *transducers* methods [6]. In the first group the initial liquid in the vessel may contain a dissolved specie which colors the solution and the added tracer combined with the solution leads to decolorization [7,8]; in the second group the tracer dispersion is followed thanks to the different tracer properties with respect to bulk liquid. In practice the tracer is suddenly added at some point of the vessel while tracer concentration time dynamics is followed by suitable sensors located in one or more other places inside vessel volume. Tracer data dynamics are then processed to extract the *mixing time*, typically defined as the time required for tracer concentration to reach within 95% of the completely mixed value. For instance, the homogenization dynamic of a concentrated electrolyte solution injection may be indirectly measured by means of conductivity probes [9], while that of a different temperature fluid injection may be assessed by means of thermometric probes [10,11]. Techniques belonging to the *transducers* group have the advantage of providing information on both circulation time, t_c, and mixing time, t_{mix}, but have the disadvantages of being intrusive (a factor that practically makes them very difficult to apply to unbaffled tanks), as well as that of relying on information in single points, rather than on the entire vessel volume.

Due to their greater industrial importance, significant attention has been devoted to baffled vessels so that experimental information on mixing time is available for these systems [5,6,12,13]. Far more limited information is presently available for unbaffled vessels [8,10,11,14]. In some of these works [8,14] the main focus is on micromixing issues and only limited information is provided on macromixing time. Other papers [10,11] concern the case of unbaffled tanks stirred by suitably offset impellers, a case where the strongly swirling motion that characterizes unbaffled tanks is more or less efficiently suppressed. Not many papers are devoted to macromixing in *vortexing* unbaffled vessels (see [10] and references therein).

In the present work mixing times in an unbaffled vessel operated without top-cover (uncovered unbaffled stirred tank, UUST) are obtained using the planar laser induced fluorescence (PLIF) technique to characterize passive tracer dispersion dynamics.

2. Experimental set-up and methods

The technique here employed is based on the analysis of images obtained by laser sheet excitation of a solution containing a fluorescent dye (Rhodamine-B). As such, it overcomes some of the limitations of other measurement techniques. In fact, apart from being quantitative and totally non-intrusive, a feature particularly desirable in unbaffled vessels, it allows the simultaneous measurement of tracer concentrations over most of the investigated plane.

For the measurements, a typical Particle Image Velocimetry and LIF-SABS [15–17] apparatus was conveniently employed. It consisted of a Nd–YAG pulsed laser source (50 mW per pulse, New-Wave Research Solo III, wavelength equal to 532 nm), coupled with a 1280 × 1024 pixel digital camera (Dantec 80C60 HiSense) and the control-synchronization unit Dantec FlowMap 1500. A high-pass filter was placed in front of the camera in order to allow only the fluoresced light (570 nm) to reach the CCD. The laser plane was focused in order to obtain a 0.5 mm thin light sheet inside the vessel.

The investigated vessel was an uncovered unbaffled cylindrical tank stirred by several centrally located impeller types, as detailed in Table 1. The vessel was 0.30 m high, while a $H_0 = T = 0.19$ m initial water filling was adopted for all experiments (water volume equal to 5.39 L). No water overflow was provided so that water could not exit from the vessel, even at the highest impeller speeds. The impeller speeds were always sufficiently low to guarantee that the deformed free-surface did not reach the impeller. Therefore the ingestion of gas bubbles that would have affected the mixing time measurement was suitably avoided. The liquid phase was deionized water at 25 °C . The cylindrical vessel was immersed in a water filled square tank, in order to minimize optical distortions due to vessel cylindrical geometry.

All impellers were placed at a clearance from the vessel bottom $C = T/3$. For the same experiments reported in Table 1 the impeller power input was experimentally measured. Details about the experimental technique adopted can be found in Scargiali et al. [18].

As concerns mixing time assessment, the technique here adopted is based on the measurement of the light re-emitted by the fluorescent dye (Rhodamine-B) suitably injected immediately above the liquid free surface by means of a hypodermic syringe. Two milliliters of a concentrated solution of Rhodamine ($C_{inj} = 12$ mg/L) were injected in each run. In this way, the final concentration of Rhodamine within the vessel was much smaller than the concentration at which photon absorption phenomena result into unacceptable light gradients in the final image ($C_{final} \cong 0.5$ mg/L). The injection point was placed at a radial coordinate $r_{inj} = 0.025$ m. Hence, the injection point is near the forced vortex region [19], a vessel region characterized by very low axial and radial velocities, *i.e.* poor mixing characteristics [8,20]. In this way, significant tracer quantities were able to enter both main region and segregated region mixing, theore leading to a thorough visualization of both zones mixing dynamics.

A preliminary masking of the laser plane was found to be advisable, in order to prevent direct laser light from hitting the deformed liquid free surface, an event that would have given rise to laser light reflection phenomena and relevant measurement disturbances.

In Fig. 1, a typical snapshot sequence as recorded during an experiment is reported. The neatly visible darker area at the top of each figure is related to laser masking meant to avoid undesired illumination of the liquid free-surface (this last is barely visible in the images due to diffuse illumination).

As it can be seen in Fig. 1, after a relatively quick internal homogenization (Fig. 1a and b), two mutually segregated zones clearly form (Fig. 1c–e): a highly concentrated small volume in between the stirrer and vortex bottom, hereafter called *segregated region*, and the rest of vessel volume (accounting for over 95% of total vessel volume) hereafter called *main region*. This observation is in agreement with previous findings by Nagata [19] and Assirelli et al. [8], who also pointed it out as a main feature of unbaffled vessel mixing performance.

Table 1
Experimental conditions.

Type	D/T	N_{min} (rpm)	N_{max} (rpm)
Rushton (6 blades)	1/3	100	450
Rushton (6 blades)	1/2	100	350
PBT (4 blades)	1/3	100	500
PBT (4 blades)	1/2	100	400
A310	1/3	200	900