ELSEVIER

Chemical Engineering Journal 72 (1999) 19–29

Chemical Engineering Journal

Feedstream jet intermittency phenomenon in a continuous stirred tank reactor

I. Houcine[a,*], E. Plasari[b], R. David[b], J. Villermaux[b]

[a] Institut National de Recherche Scientifique et Technique, Route Touristique de Soliman, B.P. 95, 2050, Hammam-Lif, Tunisia
[b] Laboratoire des Sciences du Génie Chimique CNRS - ENSIC - INPL, 1, Rue Grandville B.P. 451, 54001, Nancy, France

Received 19 December 1997; received in revised form 24 July 1998; accepted 13 August 1998

Abstract

A feedstream jet intermittency phenomenon and its onset conditions in a continuous stirred tank reactor are detected for the first time using a laser sheet induced fluorescence visualisation technique. The aim of the present investigation is to determine the operating conditions for which the intermittency phenomenon occurs in stirred tank reactors. The jet intermittency parameters studied are: stirrer type (Rushton and 45° pitched blade turbines, profiled Mixel TTP propeller), stirrer rotational speed, fluid viscosity, feeding rate and the feed point location in the tank. In the case of the Rushton turbine stirred tank reactor, diagrams of intermittency occurrence are reported. These diagrams represent the feeding jet velocity as a function of specific power input or local fluid velocity in the tank. It was not possible to derive from these diagrams any valuable correlation. In order to predict and scale-up the occurrence of intermittency in industrial stirred reactors, dimensionless correlations characterising intermittency occurrence in these devices have been modelled for the three types of stirrers. The dominant variables determining the occurrence of intermittency is the ratio of the jet velocity v_J to the tip velocity v_{tip}. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Intermittency; Feedstream jet; Jet velocity; Tip velocity

1. Introduction

Continuous stirred tank reactors are widely used in chemical process industries. For instance, precipitation, polymerisation and hydrometallurgical processes are usually carried out in such equipments. It should be emphasised that at the present state of knowledge, the fundamental understanding of turbulent mixing processes in stirred tanks has not been achieved yet. Although mixing in stirred tanks is extensively studied to understand the underlying physics of mass, momentum and energy transport and their mutual interaction, a unified understanding of turbulent mixing in these devices has not yet emerged. Fundamental studies have ranged from purely experimental investigations of mixing phenomena to their analytical/numerical simulations. Generally, experimental methods based on the use of probes (conductometric, optical, etc.) have an intrusive character modifying the course of the process under investigation. Point-wise information either in space or in time is obtained by these methods, which does not give a general view of the phenomena occurring in the stirred tank. On the other hand, classical visualisation methods using coloured substances and direct observations from outside give projected and space-averaged information which lose many aspects of fine mixing structures.

A new application of the non-intrusive laser induced fluorescence (LIF) method based on laser sheet visualisation of fluid flows and image processing has been developed to study the mechanisms of mixing in mechanically stirred tank reactors [1]. The method consists of measuring the fluorescence intensity of a tracer (e.g. rhodamine B) excited by a thin planar laser sheet and transforming it into an instantaneous concentration field of tracer by a calibration procedure [2]. This allows characterisation of mixing in a plane defined by the cross section of the flow illuminated by the laser sheet. This technique gives appreciable information about mixing and permits visualisation of new phenomena practically inaccessible to other methods. One of the most important results found by the visualisation technique is feedstream jet intermittency phenomenon in continuous stirred tank reactors. This phenomenon is demonstrated by the temporal variance field of the local concentration, which characterises the mixing dynamics in the stirred tank

---

*Corresponding author.

PII: S1385-8947(98)00124-7

[3]. The intermittency is in fact an oscillation of the feedstream jet flow through the plane of the laser sheet with a period of several seconds. The intermittent movement of the feedstream jet flow is three-dimensional, as is the flow pattern in a stirred tank, which is usually represented in a two-dimensional sketch. In fact, the term 'intermittency' is used hereafter to describe the periodical switching process of the recirculation flow between several metastable macroscopic patterns. This phenomenon is generated by the interaction between the flow induced by the stirrer and the incoming jet(s). In this sense, it differs from the phenomena called 'internal intermittency' (characterising a turbulent field) or 'external intermittency' (characterising a turbulent flow at the frontier with external irrotational flow) in fluid mechanics.

Knowledge of the cause and range of feedstream jet intermittency in stirred tank reactors is very important. In fact, this phenomenon may strongly influence the kinetics of fast chemical reactions like precipitation. In the case of precipitation processes, higher supersaturations, which are the precipitation driving forces, are induced by contact between fresh reactants of high concentration. Therefore, the intermittency of the feedstream jets may affect the precipitation kinetics appreciably, especially in double jet reactors. Also, operating irregularities may occur as in the case of experiments of micromixing characterisation by a chemical test system based on consecutive–competitive reactions in a double feed semi batch precipitator of silver bromide [4,5]. In some cases, the feedstream jet intermittency phenomenon may improve the mixing state in the stirred tank by the additional intermittent movement of the feedstream jets which contributes to homogenising the fluids in the reactor. Therefore, in future, care should be taken when designing stirred tanks for the initial contacting of two reactive species to take into account the intermittency of the feedstream jets. Many authors have proposed mixing models of incoming jets in stirred tanks for initial contacting and reaction of a reactant into a bulk fluid. Due to the limited number of available experimental data, these models remain oversimplified with respect to the complexity of the actual phenomena. In particular, no model in the literature can account for the type of intermittency described here. However, visualisation yields important and numerous information and is likely to suggest new mixing models closer to flow reality.

The occurrence of the feedstream jet intermittency in continuous stirred tank reactors may be explained by the turbulent macro-instabilities observed by several authors in stirred tank batch reactors. In fact, Winardi and Nagase [6] have detected an unstable phenomenon of flow in a mixing vessel with a marine propeller using flow visualisation and LDV techniques. Using heat flux sensors to measure heat-transfer coefficients in a mixing vessel, Haam et al. [7] have detected quasi-periodic noise which was associated to an axial vortex structure rotating in the tank. Kresta and Wood [8] and Brûha et al. [9] have discovered a macro-instability in the flow produced by a 45° pitched blade turbine in batch tank reactors. The period of this type of instability, ranging from a few to up to 10 s, is comparable with that observed in the present work for the intermittency phenomenon of the feedstream jet in a continuous stirred tank reactor. Feedstream jet intermittency has not been previously reported in the literature. The objective of the present investigation is to determine the operating conditions for which the intermittency phenomenon occurs in stirred tank reactors. The parameters studied are: stirrer type (Rushton and 45° pitched blade turbines, profiled Mixel TTP propeller), stirrer rotational speed, fluid viscosity, feeding rate and feed point location in the tank. Accordingly, diagrams of intermittency occurrence are presented. These diagrams give the feed jet velocity as a function of specific power input or local fluid velocity in the case of the Rushton turbine stirred tank reactor. Also, in order to predict and scale-up the intermittency occurrence in industrial stirred reactors, dimensionless correlations characterising the onset of intermittency in these devices have been determined for the three types of stirrers used in this work.

2. Experimental technique

The experimental set-up used in this work is described by Fig. 1. The experiments were carried out in a mechanically stirred tank of 20 dm^3 volume (see Fig. 2). The tank was made of an inner cylindrical vessel of internal diameter $T = 0.288$ m and a conical bottom placed in an outer square tank. Both vessels were made of a transparent material (altuglas of optical quality) and the spacing between them was filled with water so as to reduce the light deviation by the interfaces. The tank was fitted with four removable baffles $T/10$ wide and stirred with three different types of stirrers namely a Rushton turbine ($D = T/3$), a 45° pitched-blade turbine ($D = 0.4\ T$) and a profiled Mixel TTP propeller ($D = 0.4T$) (see Fig. 3). The stirrers were placed at a clearance from the tank bottom of $h = H/3$, where H represents the height of the liquid in the tank. The stirring speed was varied in a range ($100 \leq N \leq 500$ rpm) corresponding to a turbulent flow regime. Two independent reservoirs continuously supplied the tank with the same flow rates (space times: $3.5 \leq \tau \leq 6$ min) by the mean of two incoming jets (jet tube internal diameter = 4, 7 and 10 mm). Accordingly, the injection jet velocity v_J ranged between 0.1 and 2.8 $\mathrm{m\ s^{-1}}$. The feed points were located in six symmetrical positions in the laser sheet covering all regions of the tank: in the radial and axial discharge streams close to the stirrer and in the bulk zones (see Fig. 2). One of the feedstream fluids was a rhodamine B solution, whereas the other was pure water. Rhodamine B was selected as the fluorescent tracer given its high quantum yield, its remarkable chemical stability when exposed to the laser beam and its linear elementary response of fluorescence with respect to concentration [1]. The fluid viscosity was varied by

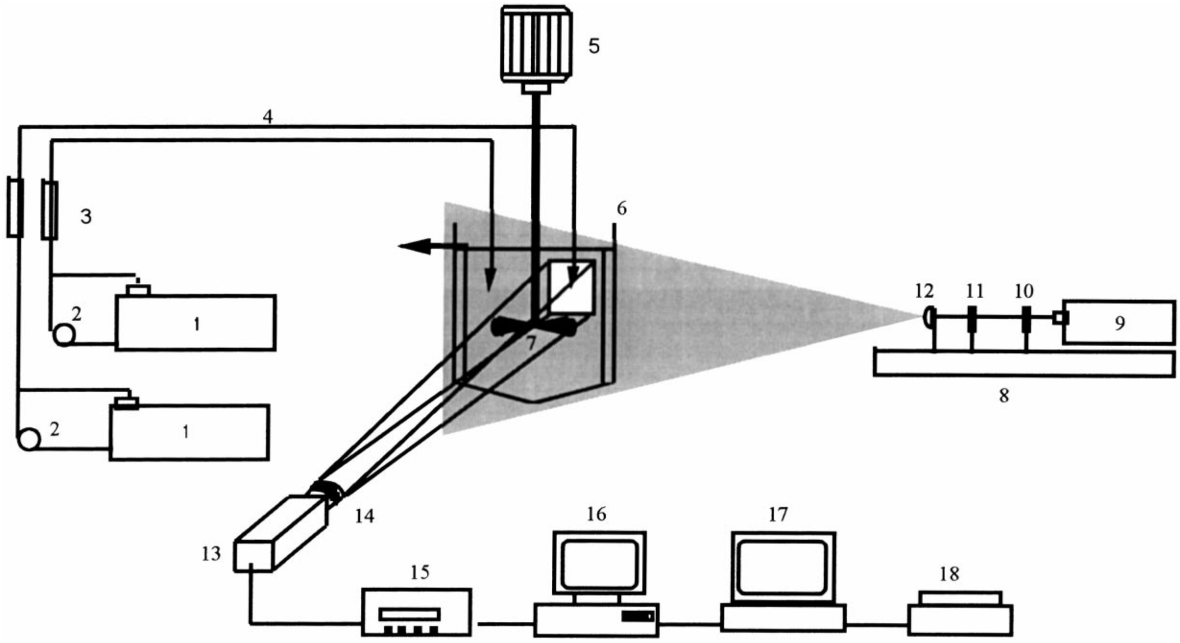


Fig. 1. Experimental set-up 1. Reservoir (1 m^3), 2. Pump, 3. Flow meter, 4. Feed tubes, 5. Reducing motor, 6. Mixing tank (20 dm^3), 7. Stirrer, 8. Optical bench-table, 9. Water-cooled Argon ion laser (power 1.4 W at 514 nm), 10. Plano-convex lens, 11. Plano-concave lens, 12. Cylindrical lens ($f = 22.2$ nm), 13. CCD camera (sensibility: 0.25 lx), 14. Sharp cut-off filter (560 nm), 15. Magnetic tape recorder, 16. Computer (image processing), 17. Color graphics display unit, 18. Printer.

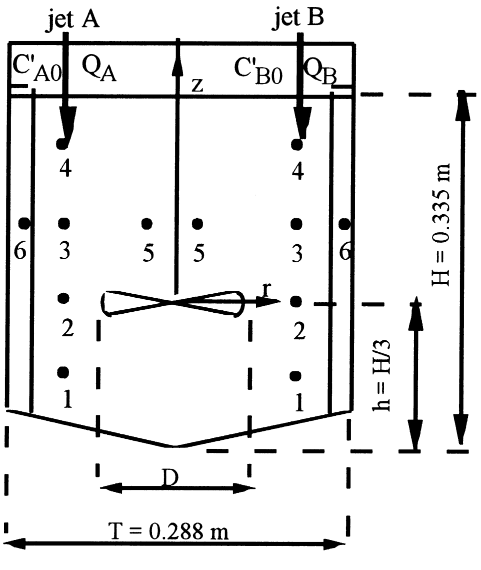


Fig. 2. Mixing tank and feeding point location ⟨1-1⟩ ··· ⟨6-6⟩.

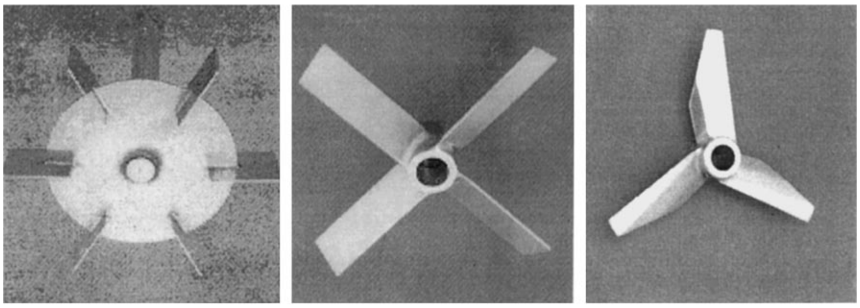
dissolving polyethylene glycol in water up to $\mu = 4 \times 10^{-3}$ Pa s.

The beam of an Argon-ion laser operating in light-stabilised mode at a wavelength of 514 nm (power: 1.4 W) was formed into a sheet of 0.5 mm mean thickness using a plano-convex lens, a plano-concave lens and a cylindrical lens. The molecules of rhodamine B, excited by the laser sheet, emit a fluorescent light at wavelengths centred around 590 nm. The laser induced fluorescence (LIF) from the zone under investigation was viewed by a CCD camera of sensitivity 0.25 lx and exposure time 40 ms equipped with a sharp cut-off filter successfully blocking out any incident scattered light below 560 nm. The field of view of the camera covered an area of 31 mm × 21 mm such that the zone of water feeding jet was seen in its entirety (see Fig. 1). The images were recorded by a semi-professional video tape recorder. The videotape was scanned and digitised into 256 grey levels through a commercial package at a rate of one image per second. The digitised LIF images (512×512 pixels, rectangular grid) were processed by means of a locally developed software on a colour display workstation connected to the laboratory network.

3. Results and discussion

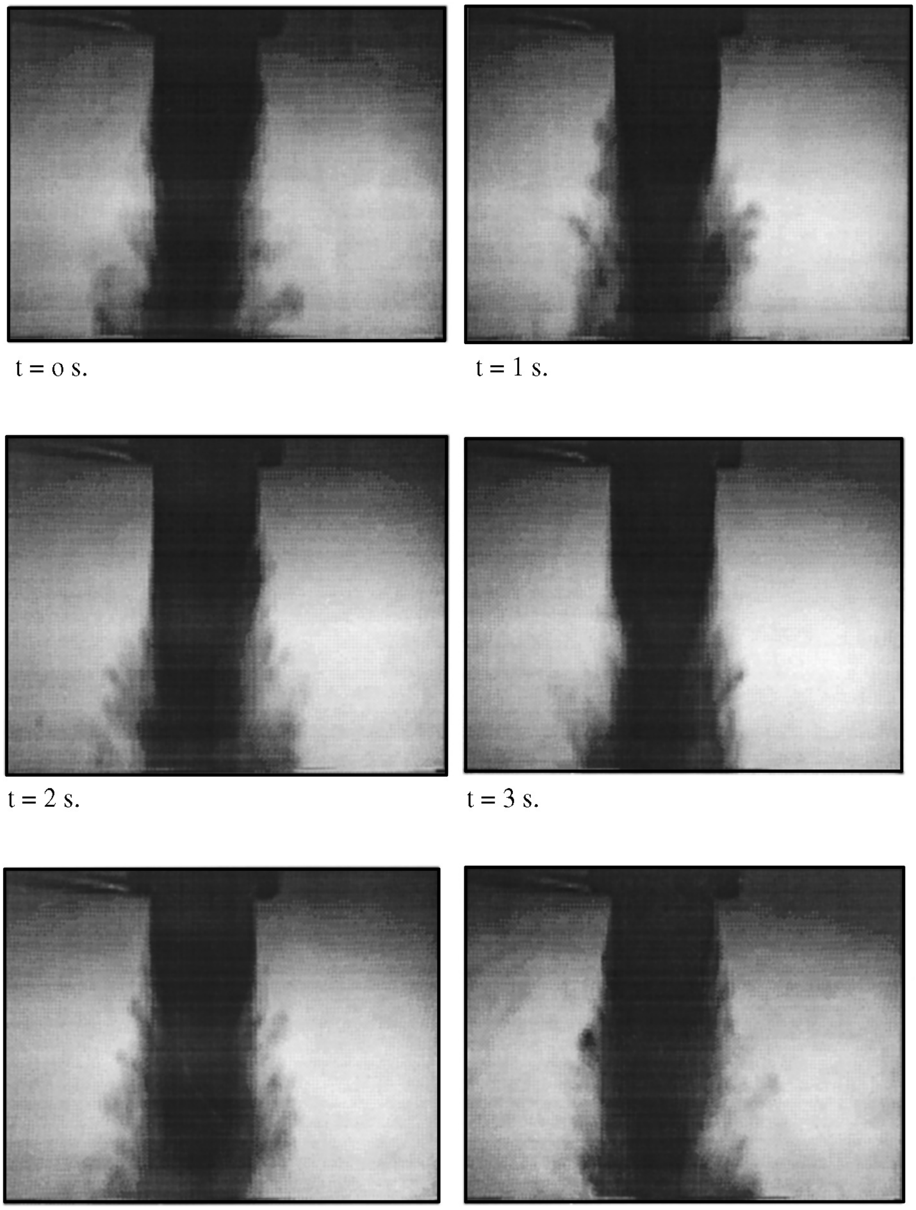
For each experiment, intermittency is determined from the LIF images. The intermittency is characterised by oscillation of the feedstream jet flow in the plane of the laser sheet. For each experiment, three cases can be encountered:

- no intermittency (the feedstream jet axis is always vertical (see Fig. 4);
- appearance of slight intermittency characterised by a chaotic movement of the feedstream jet axis in the plane of the laser sheet with a period ranging from 3 to 4 s (see Fig. 5);
- effective intermittency with a smaller period than the above case (1–2 s, see Fig. 6).



(a) Rushton turbine (b) pitched-blade turbine (c) MIXEL TTP propeller

Fig. 3. Mixing stirrers.

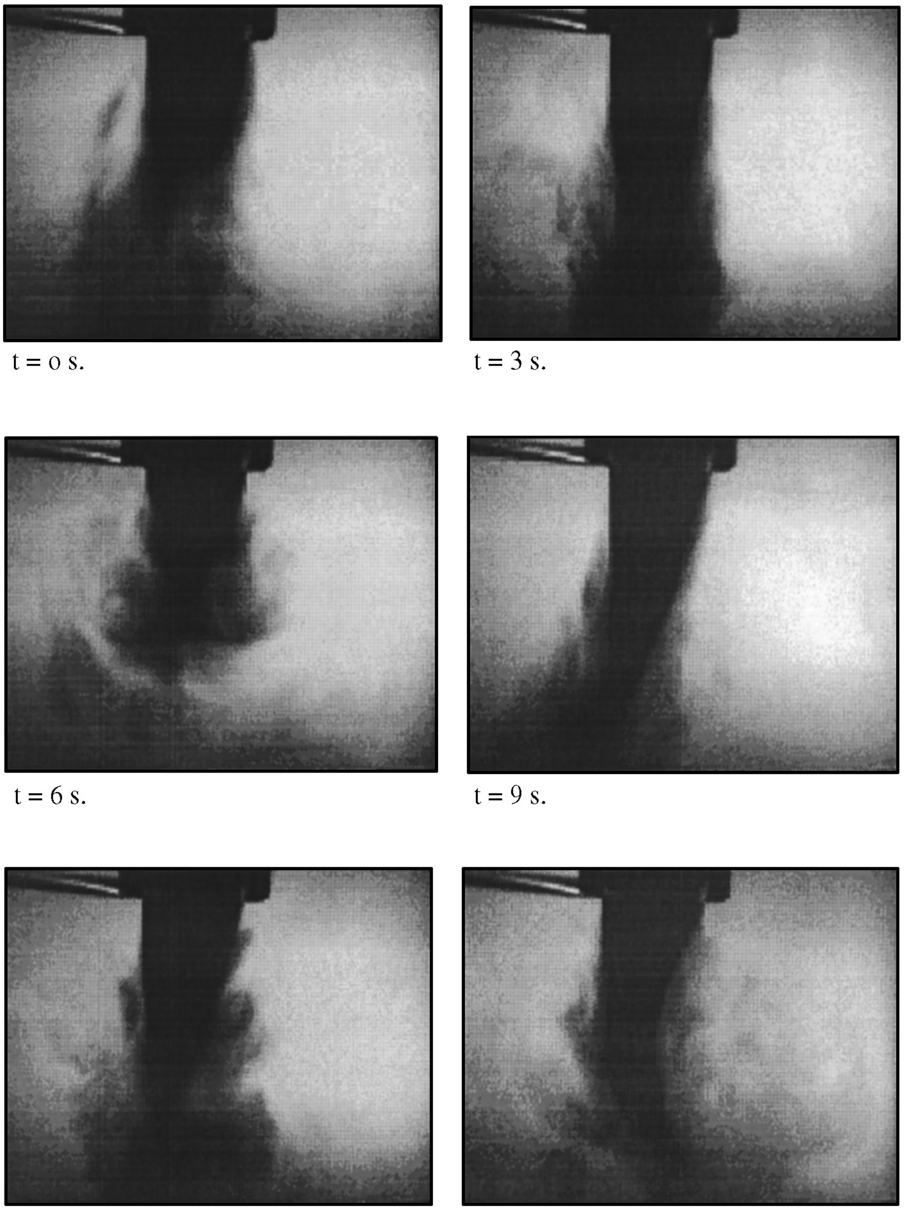


t = 0 s. t = 1 s.

t = 2 s. t = 3 s.

t = 4 s. t = 5 s.

Fig. 4. Instantaneous digital LIF images for Rushton turbine: no intermittency ($D = T/3$, $h = H/3$, $V_J = 0.6$ m s^{-1}, $N = 112$ rpm, $\mu = 10^{-3}$ Pa s, $d_t = 7$ mm, feed position $\langle 6\text{-}6 \rangle$).



t = 0 s.

t = 3 s.

t = 6 s.

t = 9 s.

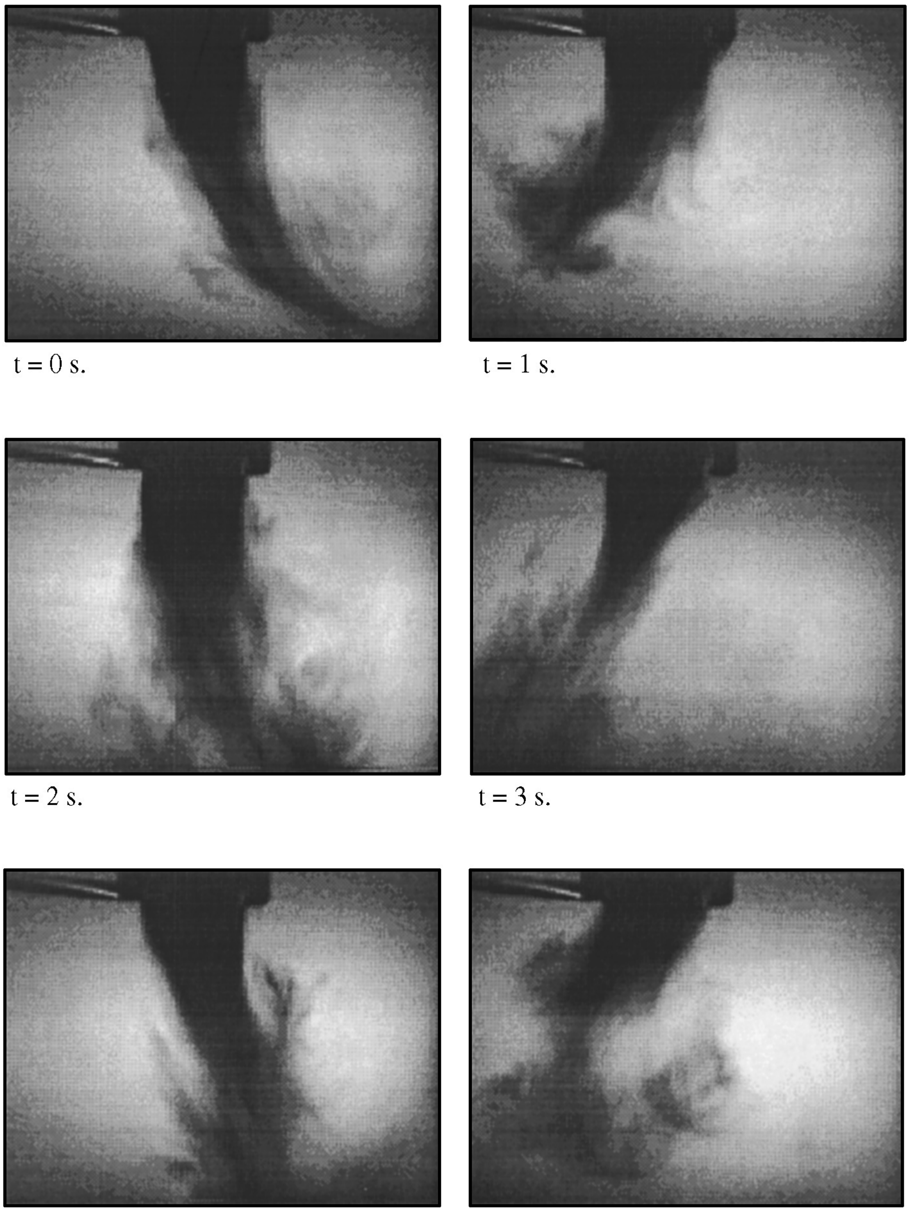
t = 12 s.

t = 15 s.

Fig. 5. Instantaneous digital LIF images for Rushton turbine: slight intermittency ($D = T/3$, $h = H/3$, $v_J = 0.6\ \mathrm{m\ s^{-1}}$, $N = 112$ rpm, $\mu = 10^{-3}$ Pa s, $d_t = 7$ mm, feed position $\langle 6\text{-}6 \rangle$).

Fig. 7 shows a typical example of experimental results obtained in the case of Rushton turbine stirred tank ($D = T/3$, $h = H/3$, $\mu = 10^{-3}$ Pa s, $d_t = 7$ mm) continuously fed in location $\langle 3\text{-}3 \rangle$. It can be seen that the range of slight intermittency is narrow, demonstrating that for a given geometrical tank configuration, fluid properties and injector jet velocity v_J, the transition between no-intermittency and effective intermittency often occurs within a range of impeller rotational speed narrower than 50 rpm. This result proves that the impeller rotational speed is one of the most important factors controlling the intermittency occurrence in continuously stirred tank reactors.

A first qualitative comparison of the experimental results show that intermittency is encountered more often in the case of the pitched blade turbine and Mixel TTP propeller. We have also noticed that with the present operating conditions there is no intermittency for position $\langle 2\text{-}2 \rangle$ in the case of Rushton turbine stirred tank. These results are in agreement with the hypothesis established by several authors [8,9] saying that macro-instability occurs in batch tank reactors as a consequence of the existence of a ‘double loop’ flow in an axially stirred tank (such as pitched blade turbine and Mixel propeller) in addition to the classical ‘single loop’ one. In this case, the occurrence of the



t = 0 s.

t = 1 s.

t = 2 s.

t = 3 s.

t = 4 s.

t = 5 s.

Fig. 6. Instantaneous digital LIF images for Rushton turbine: effective intermittency ($D = T/3$, $h = H/3$, $v_j = 0.6\ \mathrm{m\ s^{-1}}$, $N = 112$ rpm, $\mu = 10^{-3}$ Pa s, $d_t = 7$ mm, feed position ($\langle 6\text{-}6 \rangle$)).

turbulent macro-instability is caused by the transition between the single loop and double loop flow patterns, whereas in the case of Rushton turbine stirred tank, the flow patterns are more uniform (mostly double loop only) and consequently the occurrence of intermittency is lower.

It is interesting to note that in the case of a continuous stirred tank reactor, the occurrence of the feedstream jet intermittency phenomenon is due to the confrontation between the feedstream jet and the chaotic movement of the flow patterns in the tank. In fact, the flows generated by the stirrer in the tank can create a chaotic movement, but the feedstream jet may have a high kinetic energy input leading to jet stability. As a result, for a given mixing tank configuration and fluid properties, both characteristics of the feedstream jet (injector tube diameter d_t, injection jet velocity v_J) and the impeller flow (rotational speed, local fluid flow characteristics) may be important factors governing the occurrence of intermittency in continuously stirred tank reactors.

4. Relationship between occurrence of intermittency and local characteristics of fluid flow

In the case of the standard Rushton turbine stirred tank reactor, local characteristics of fluid flow are extensively

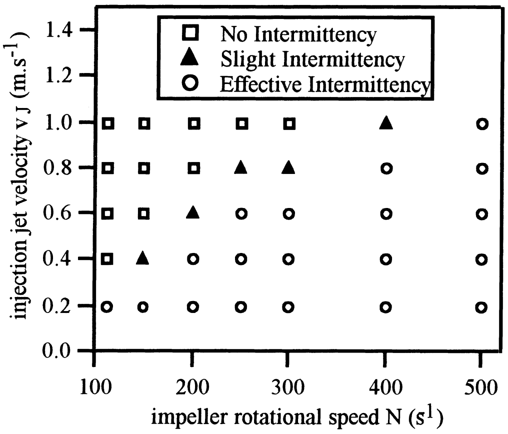


Fig. 7. Typical example of experimental results (feed points ⟨3-3⟩, $D = T/3$, $h = H/3$, $\mu = 10^{-3}$ Pa s, $d_t = 7$ mm).

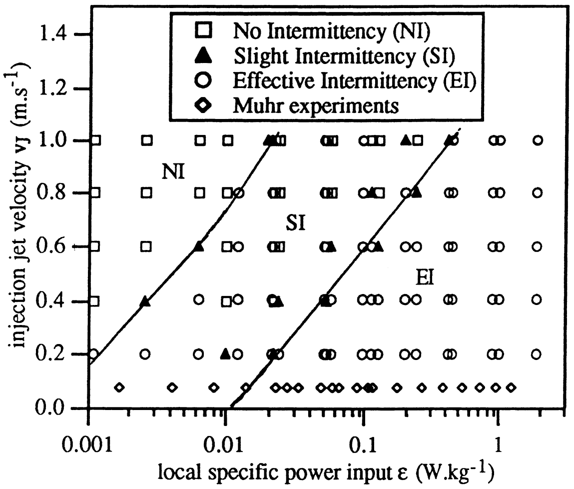


Fig. 8. Feeding jet velocity v_J vs. specific power input ε for Rushton turbine.

investigated in view of both experimental measurements and mathematical modelling. In order to predict the operating conditions where the feedstream jet intermittency phenomenon occurs in the Rushton turbine stirred tank, diagrams representing feeding jet velocity v_J as a function of specific power input ε or local fluid velocity v can be proposed.

The local specific power input ε is related to the average power consumption per unit mass of fluid $\bar{\varepsilon}$ dissipated in the tank:

$$\varepsilon = \phi\bar{\varepsilon} \qquad (1)$$

where

$$\bar{\varepsilon} = N_P \frac{N^3 D^5}{V_R} \qquad (2)$$

The power number N_P is equal to 5.44 for Rushton turbine, 1.25 for 45° pitched-blade turbine and 0.4 for Mixel TTP propeller [10].

The local velocity v of the fluid projected on the plane of the laser sheet is given by

$$v = \sqrt{U^2 + V^2} \qquad (3)$$

where the mean radial (U) and axial (V) velocities are given by their dimensionless expressions:

$$U^* = \frac{U}{\pi N D} \quad \text{(dimensionless)} \qquad (4)$$

$$V^* = \frac{V}{\pi N D} \quad \text{(dimensionless)} \qquad (5)$$

In the case of Rushton turbine stirred tank reactor of standard configuration, the specific energy dissipation rate ϕ and the dimensionless mean velocities (U^*, V^*) are given for each feed point location by correlations established by Bourne and Yu [11]. It should be emphasised that, although the local characteristics of fluid flow (ϕ, U^*, V^*) were derived based on experimental results in the literature, the values of ϕ, U^* and V^* obtained by Bourne and Yu [11] only approximately represent the average flow characteristics in the stirred tank since the flow model was formulated by assuming six characteristic flow regions and one streamline plug flow through the regions. Of course, these assumptions simplify the complexity of the real flow in the stirred tank.

In the case of Rushton turbine stirred tank, experimental results of runs carried out with feedstreams of pure water and dye solution respectively ($\mu = 10^{-3}$ Pa s) have been reported in a diagram representing the feeding jet velocity v_J as a function of specific power input ε for all feed point locations except position ⟨2-2⟩ (see Fig. 2) for which no intermittency was observed under the present operating conditions (see Fig. 8). In the same manner, the feeding jet velocity v_J is plotted against local fluid velocity v in Fig. 9. From these figures, we see that the zone of transition (appearance of slight intermittency of lower frequencies) is not sharply limited. In fact, the transition region presents an overlap of the three cases encountered (no intermittency,

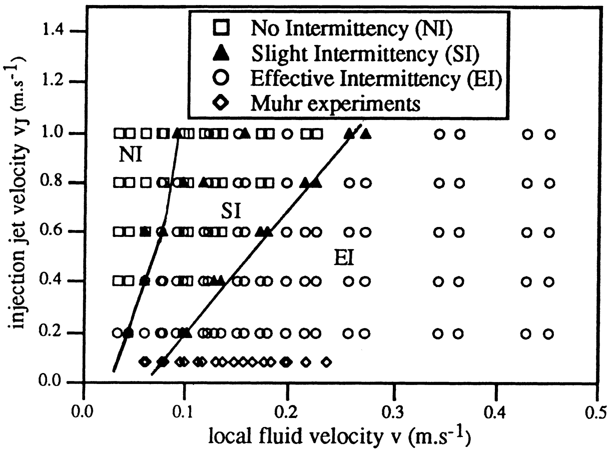


Fig. 9. Feeding jet velocity v_J vs. local fluid velocity v for Rushton turbine.

appearance of slight intermittency and effective intermittency). Thus, an approximate delimitation has been done permitting to point out with certitude the operating conditions of both no-intermittency and effective intermittency zones. The relations between the injection jet velocity and the norm of the projected local fluid velocity or the local specific power input in the tank are interesting for the prediction of the intermittency occurrence in stirred tanks, but are not the main factors controlling the intermittency occurrence in continuously stirred tank reactors. In fact, unlike the transition range (appearance of slight intermittencies) shown in Fig. 7 which was found to be narrow and clearly established, the (v_J–ε) and (v_J–v) diagrams do not present a clear transition range. This may be the result of the approximation made in the determination of the local characteristics of fluid flow (ϕ, U^*, V^*) and thus the accuracy of the (v_J–ε) and (v_J–v) diagrams might be affected by these errors. Nevertheless, these observations suggest that the impeller rotational speed is more significant than the local characteristics of fluid flow for the prediction of the intermittency occurrence in stirred tanks.

The (v_J–ε) or (v_J–v) diagrams can be used in predicting the operating conditions in which the feedstream jet intermittency occurs. For example, David et al. [4] observed irregularities in experiments characterising micromixing using a chemical test reaction in a double feed semi batch precipitator of silver bromide. The test system was the classical diazo-coupling consecutive-competitive reaction ($A + B \rightarrow R$; $R + B \rightarrow S$; Bourne et al. [12]). The segregation index X_S was given by the final concentrations of reactant dyes R and S determined after completion of feeding and reaction: $X_S = 2C_S/(2\,C_S + C_R)$. The feed point locations in the tank were similar to those tested in the present investigation. The details of the experimental results of the micromixing characterisation in both single feed and double feed semi-batch reactors are reported in the literature [4,5]. It was found that the segregation index X_S presents oscillations with variation of the stirring speed for the double jet reactor and for all feed point locations except position ⟨2-2⟩ (the oscillations are negligible). On the other hand, experiments conducted in single jet reactor with the same hydrodynamic conditions and feeding points show that the segregation index X_S decreases monotonously with an increase of the stirring speed [5]. The results found in double feed semi-batch reactor can be explained by a jet intermittency effect. In fact, the experimental operating conditions of Muhr et al. [4,5] were all situated in transition and effective intermittency zones of the (v_J–ε) and (v_J–v) diagrams (see Figs. 8 and 9). Although the experiments conducted by Muhr et al. [5] in single jet feeding reactor were with the same hydrodynamic conditions and feeding points as those carried out in the double feed reactor, the former tank configuration does not present oscillations of the segregation index X_S. In this case, the fresh reactant carried by the injector is always in contact with the bulk fluid. In the case of double feed reactor, the two fresh reactants carried by the injectors may be brought into contact together or both with the bulk fluid when intermittency takes place leading to oscillations in the segregation index X_S.

In future work, intermittency should be taken into account. In fact, the present investigation has shown that the intermittency phenomenon is frequently found in stirred tanks. In order to confirm this new finding, Marcant and Seuron [13] have detected the same feedstream jet intermittency phenomenon in a 150 dm^3 stirred tank using the same laser sheet visualisation technique.

5. Dimensional analysis of the intermittency occurrence

In order to predict the occurrence of intermittency in industrial stirred tanks, dimensional analysis was used to characterise the intermittency in these devices. The range of slight intermittency is considered as the transition range between no-intermittency and effective intermittency ranges. The slight intermittencies have been visually characterised by an appearance of a chaotic movement of the feedstream jet axis in the plane of the laser sheet (in the case of no intermittency, the feedstream jet axis is always vertical) and by frequencies lower than those of effective intermittency (see Figs. 5 and 6). Therefore, the criterion of intermittency observation is the variation of the angle α between the feedstream jet axis and the axis of the feeding tube.

For a given stirrer, the variation of the angle α depends on fluid properties and on the geometrical parameters of the mixing device and can be expressed by a Buckingham Π equation:

$$\Delta\alpha = kN^{C1} v_J^{C2} \mu^{C3} \rho^{C4} D^{C5} T^{C6} d_t^{C7} \tag{6}$$

where k depends on the feed point location.

The theoretical analysis (M,L,T) reduces the above equation to

$$\Delta\alpha = k\left(\frac{v_J}{ND}\right)^{x1}\left(\frac{\rho N D^2}{\mu}\right)^{x2}\left(\frac{d_t}{D}\right)^{x3} \tag{7}$$

The slight intermittencies have been approximately characterised by the same variation of angle α, and expression (7) can then be reduced to

$$\frac{v_J}{\pi N D} = k'\left(\frac{\rho N D^2}{\mu}\right)^{c1}\left(\frac{d_t}{D}\right)^{c2} \tag{8}$$

where the dimensionless constant k' depends on the feed point location.

Three basic dimensionless groups appear from this theoretical analysis. The first dimensionless group is $v_J/\pi ND$, which represents the ratio between injection velocity v_J and impeller tip tangential velocity v_{tip} , the second is the stirrer Reynolds number, $\rho ND^2/\mu$, which is a useful parameter characterising the flow behaviour in the tank and the third is a geometric ratio, d_t/D, which accounts for the effect of injector tube diameter.

The multilinear regression of the experimental data for each configuration of impeller stirred tank has shown that the variation of the dimensionless constant k' with the feed point location is negligible. Accordingly, the correlations obtained by the above dimensional analysis are:

for Rushton turbine:

$$\frac{v_J}{v_{tip}} = 11.87\,\mathrm{Re}^{-0.47}\left(\frac{d_t}{D}\right)^{-0.73} \qquad (9)$$

where $0.40 \le v_J/v_{tip} \le 2.65$; $6 \times 10^3 \le \mathrm{Re} \le 41 \times 10^3$; $0.04 \le d_t/D \le 0.10$;

for 45° pitched blade turbine:

$$\frac{v_J}{v_{tip}} = 4.84\,\mathrm{Re}^{-0.48}\left(\frac{d_t}{D}\right)^{-1.02} \qquad (10)$$

where $0.16 \le (v_J/v_{tip}) \le 2.21$; $8 \times 10^3 \le \mathrm{Re} \le 48 \times 10^3$; $0.03 \le d_t/D \le 0.09$;

for Mixel TTP propeller:

$$\frac{v_J}{v_{tip}} = 4.00\,\mathrm{Re}^{-0.45}\left(\frac{d_t}{D}\right)^{-0.94} \qquad (11)$$

where $0.16 \le v_J/v_{tip} \le 2.21$; $8 \times 10^3 \le \mathrm{Re} \le 68 \times 10^3$; $0.03 \le d_t/D \le 0.09$.

These equations (Eqs. (9)–(11)) given for each type of stirrer are very important for the prediction of intermittency in stirred tank reactors. In fact, if the left-hand side is inferior to the right-hand side (LHS < RHS), intermittency will be observed.

The data presented in Figs. 10–12 for each type of stirrer produce a straight line relationship with some scatter (mean relative error <7%) due to the approximation of negligible variation of the dimensionless constant k' with the feed point location. The above correlations given for each type of stirrer (Eqs. (9)–(11)) relate between dimensionless classical groups, such as stirrer Reynolds number, and do not require determination of additional parameters as in the case of the (v_J–ε) and (v_J–v) diagrams. Also, contrary to the transition range shown in Fig. 8 and Fig. 9 of the (v_J–ε) and (v_J–v) diagrams which were found to be not clearly established, the correlations represented in Figs. 10–12 are a sharp limiting mean between the no-intermittency and effective intermittency ranges. For example, in the case of Rushton turbine stirred tank reactor, the experimental operating conditions of Muhr et al. [4,5] are now all situated in the effective intermittency zone of the Fig. 10

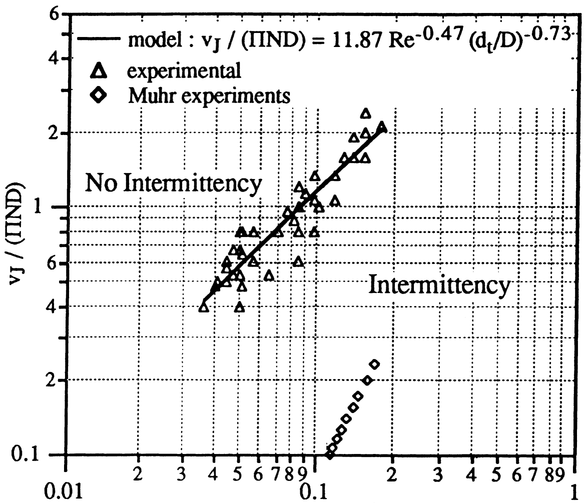


Fig. 10. (v_J/v_{tip}) vs. $\mathrm{Re}^{c1} \times (d_t/D)^{c2}$ for transition from steady to intermittent flows (Rushton turbine).

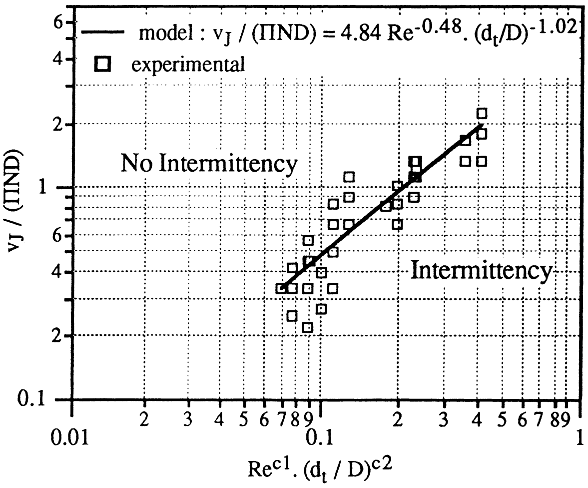


Fig. 11. (v_J/v_{tip}) vs. $\mathrm{Re}^{c1} \times (d_t/D)^{c2}$ for transition from steady to intermittent flows (45° pitched turbine).

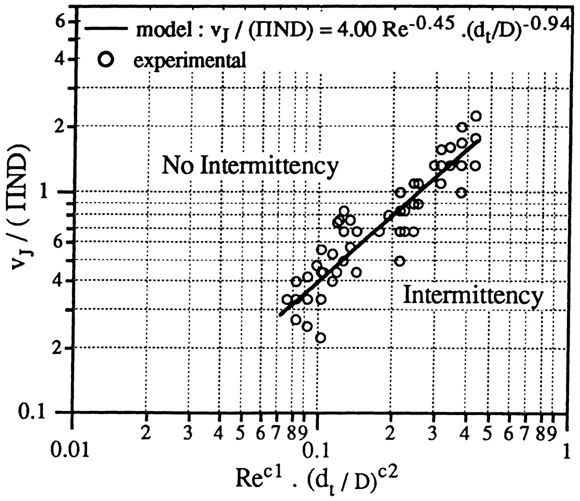


Fig. 12. (v_J/v_{tip}) vs. $\mathrm{Re}^{c1} \times (d_t/D)^{c2}$ for transition from steady to intermittent flows (Mixel propeller).

In chemical processes, production units are usually built at large scale. Although, the scale-up effects were not experimentally checked during our runs, we have tried to estimate these effects. The above correlations established in a rather small vessel unit (tank volume: 20 dm^3) are expected to remain valid in large vessels. In general, for continuous stirred tanks, a practical scale-up is based on constant average energy dissipated per unit mass of fluid $\bar{\varepsilon}$ constant mean residence time in the tank τ and constant injection jet velocity v_J.

Preservation of $\bar{\varepsilon}$ constant during scale up (assuming exact geometric similarity) yields

$$\bar{\varepsilon} = \frac{N_P N^3 D^5}{V_R} \propto \frac{N_P N^3 D^5}{D^3} \propto N^3 D^2 = \text{const} \tag{12}$$

$$N \propto D^{-2/3} \tag{13}$$

Taking into account Eq. (13) and preserving v_J constant during scale up yields

$$\frac{v_J}{ND} \propto D^{-1/3} \tag{14}$$

Preserving τ and v_J constant during scale up yields

$$\tau = \frac{V_R}{Q} \propto \frac{D^3}{d_t^2} = \text{const} \tag{15}$$

$$d_t \propto D^{3/2} \tag{16}$$

In the case of the Rushton turbine stirred tank reactor, taking into account Eqs. (13) and (16) gives

$$\left(\frac{\rho N D^2}{\mu}\right)^{-0.47} \left(\frac{d_t}{D}\right)^{0.73} \propto D^{-1} \tag{17}$$

Eqs. (14) and (17) imply that the zone of effective intermittency decreases during scale-up at constant $\bar{\varepsilon}$, τ and v_J. This result is in agreement with the experimental observations done in a 150 dm^3 stirred tank by Marcant and Seuron [13]. Thus, based on these remarks and on the scale-up theoretical analysis given above, the feedstream jet intermittency phenomenon in large industrial stirred tanks can be less important than the present experimental investigation. The dimensionless correlations given above are conservative for the prediction of the intermittency occurrence in industrial stirred reactors since intermittency is overestimated by these correlations.

6. Conclusions

In the present investigation, the discovery of feedstream jet intermittency in a continuous stirred tank reactor has been described based on the study of turbulent mixing by means of a laser induced fluorescence visualisation technique. The operating conditions (stirrer type, impeller rotational speed, fluid viscosity, feeding rate and feed point location in the tank) under which the intermittency phenomenon occurs in stirred tank reactors have been determined and displayed in jet velocity vs. impeller rotational speed (v_J–N) diagrams. In the case of the Rushton turbine stirred tank reactor, diagrams of intermittency occurrence were developed. These diagrams represent feeding jet velocity as a function of specific power input or local fluid velocity in the tank. The demarcation between intermittency and non-intermittency was not as clearly indicated in these as in the (v_J–N) diagrams. In order to predict and scale-up the occurrence of intermittency in industrial stirred reactors, dimensionless correlations characterising intermittency occurrence in these devices were derived for the three types of stirrers used in this work (Rushton and 45° pitched blade turbines, Mixel TTP propeller).

Further research will take place in order to study the influence of other operating conditions (stirrer diameter, tank diameter, impeller clearance, liquid height, number of agitator blades, etc.) on the occurrence of the feedstream jet intermittency phenomenon in stirred tanks. It is expected that experiments of chemical test reactions will be carried out in order to perform this investigation.

In future studies of continuous stirred tank reactors, one should take into account intermittency as an important factor. Clearly, the present investigation has shown that the intermittency phenomenon is frequently found in stirred tanks. New mixing models, which take into account this phenomenon and thus become more and more representative of the whole real mixing process in stirred tanks, have to be proposed accordingly.

7. Nomenclature

C	fluorescent dye concentration, mol m^{-3}
D	stirrer diameter, m
d_t	injector tube diameter, m
h	stirrer clearance from tank bottom, m
H	height of the liquid in the tank, m
N	stirrer rotational speed, s^{-1}
N_P	stirrer power number
Q	volumetric flow rate, m^3 s^{-1}
Re	stirrer Reynolds number, $\rho ND^2/\mu$
T	tank diameter, m
t	time, s
U	mean radial velocity, m s^{-1}
V	mean axial velocity, m s^{-1}
v	local fluid velocity, m s^{-1}
v_J	injection jet velocity, m s^{-1}
v_{tip}	impeller tip tangential velocity, πND, m s^{-1}
V_R	reactor volume, m^3
ε	local specific power input, W kg^{-1}
$\bar{\varepsilon}$	average power cosumption per unit mass of liquid, W kg^{-1}
ϕ	specific energy dissipation rate
μ	fluid viscosity, Pa s
ρ	fluid density, kg.m^{-3};
τ	mean residence time in the tank, s

Acknowledgements

This work was carried out with the financial support of the French Ministry of Higher Education and Research. As

Prof. Jacques Villermaux passed away prior to the completion of this paper, the other co-authors wish to dedicate this work in his memory. Prof. Jacques Villermaux had, during his life, contributed much to the progress of chemical engineering world wide, especially in the field of chemical engineering reaction and mixing.

References

[1] I. Houcine, H. Vivier, E. Plasari, R. David, J. Villermaux, Characterisation of mixing in stirred tanks by laser sheet visualisation and image processing method. in: Proc. 11th Int. CHISA '93, Praha, 1993, Paper 197.

[2] I. Houcine, H. Vivier, E. Plasari, R. David, J. Villermaux, Planar laser induced fluorescence technique for measurements of concentration fields in continuous stirred tank reactors, Exp. Fluids 22 (1996) 95–102.

[3] I. Houcine, H. Vivier, E. Plasari, R. David, J. Villermaux, Comparison of mixing action of several stirrers by laser sheet visualisation and image processing. in: 8th European Conf. on Mixing, 21–23 September 1994, Cambridge, UK, IChemE Symp. Series, 136 (1994) 97–104.

[4] R. David, H. Muhr, J. Villermaux, The yield of a consecutive–competitive reaction in a double jet semi-batch reactor: comparison between experiments and a multizone mixing model, Chem. Eng. Sci. 47 (1992) 2841–2846.

[5] H. Muhr, R. David, J. Villermaux, Determination of the state of micromixing in a stirred tank reactor by means of consecutive-competitive reactions and interpretation of experimental data by different models, in: AIChE Annual Meeting, Chicago, 1990.

[6] S. Winardi, Y. Nagase, Unstable phenomenon of flow in a mixing vessel with a marine propeller, J. Chem. Eng. Japan 24 (1991) 243–249.

[7] S. Haam, R.S. Brodkey, J. Fasano, Local heat transfer in mixing vessel using heat flux sensors, Ind. Eng. Chem. Res. 31 (1992) 1384–1391.

[8] S.M. Kresta, P.E. Wood, The mean flow field produced by a 45° pitched blade turbine: changes in the circulation pattern due to off bottom clearance, Can. J. Chem. Eng. 71 (1993) 42–53.

[9] O. Brûha, I. Fort, P. Smolka, Flow transition phenomenon in an axially agitated system, Proc. 8th European Conf. on Mixing, Cambridge, UK, 1994, pp. 121–128.

[10] I. Houcine, Etude du mélange dans une cuve agitée de taille pilote – Application à la précipitation de l'oxalate de calcium, Ph.D. Thesis, 1995, Institut National Polytechnique de Lonaire Nancy, France.

[11] J.R. Bourne, S. Yu, Investigation of micromixing in stirred tank reactors using parallel reactions, Ind. Eng. Chem. Res. 33 (1994) 41–55.

[12] J.R. Bourne, C. Hilber, G. Tovstiga, Kinetics of the azo-coupling reactions between 1-naphtol and diazotised sulphanilic acid, Chem. Eng. Commun. 37 (1985) 293–314.

[13] B. Marcant, L. Seuron, Evaluation des performances du mélange en réacteur agité par la méthode de fluorescence en nappe laser, Rhône-Poulenc internal communication, 1993.