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EFFICIENCY IMPROVEMENT OF A TUBULAR JET REACTOR BY MIXING INCREASE

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A logical and progressive method is proposed to modify and increase the performance of chemical reactors where the main inner process is mixing. This method includes global analysis based on mixing visualization, followed by local value measurements. This article reports the case of an axisymmetrical tubular jet mixer: turbulent mixing is speeded up by means of a swirling jet.

Keywords: mixing; turbulence; tubular reactor; axisymmetrical jet; swirling jet

INTRODUCTION

This work reports a general and progressive approach of efficiency enhancement for instantaneous kinetic reactors through an industrial example: a tubular axisymmetrical jet-stirred reactor that runs under turbulent flow regime. It belongs to Elf-Atochem and produces fertilizers on 'La Grande Paroisse' society production units.

In this case of very fast or 'instantaneous' reactions, the efficiency enhancement closely depends on the mixing performance of the reactor. The first step of the present approach is to consider solutions that would improve this performance. Mixing rate is analysed for these configurations by the means of laser techniques in glass pilots. Experiments are carried out with water; they first consist of global visualizations of mixer behaviour that put the less interesting solutions aside and bring to the fore the main parameters. Effectiveness of the best configurations is then precisely checked through a local investigation of the reactor. Their performance is compared to that of the classical reactor taken in the same operating conditions. The final solution is then tested on production site.

AXISYMMETRICAL JET MIXER AMELIORATION PROPOSALS

Mixing is clearly related to the turbulence level, as is the efficiency of the reactor. Mean convection, turbulent and molecular diffusions simultaneously take place in a turbulent flow¹. Turbulence is particularly developed in stress zones of the flow where momentum gradients are strong.

In an axisymmetrical reactor, turbulence is induced at the jet periphery². It may be amplified by the addition of an obstacle in the stress zone around the jet³, especially by a sharp edge that breaks eddies and destabilizes the turbulent zone up to its point of generation^{4,5}.

Particular attention must be paid to swirling jets: they

promote mixing by creating tangential shear stress all around, whose action, added to that of classical axial stress, leads to a larger jet expansion towards reactor main wall and to higher turbulence intensity. A direct consequence is that a shorter axial mixing length⁶ is needed.

In the light of the preceding analysis, two easy-to-fit modifications are proposed to improve the reactor:

- (1) an axisymmetrical baffle, or 'diaphragm', to be placed inside the mixer in such an axial position that the stress zone around the jet could be broken; the inner diameter must be large enough to induce mild pressure loss only;
- (2) a swirling jet that creates additional shear stress; swirl may be generated by the means of a helicoidal twisted tape settled inside the nozzle.

These two static mixers, and also combinations of them, are to be tested on an experimental plant.

EXPERIMENTAL EQUIPMENT

The chosen experimental techniques are optical ones to keep the flow out of any probe disturbance; the pilot is thus made of glass tubing.

Axisymmetrical Jet-stirred Reactor

The reactor itself consists of a horizontal glass tube of inner radius $R_1 = 25 \cdot 10^{-3}$ m, and length $L = 1.8$ m (Figure 1). This tube lays in a rectangular glass box full of water, allowing the laser rays to propagate from air to water without disturbance⁷.

The nozzle is an aluminium tube (inner radius $R_0 = 5 \cdot 10^{-3}$ m) and is perfectly centred inside the reactor.

The inlet velocities U_0 and U_1 of the jet and its secondary flow respectively vary from 0.3 to 14 m s⁻¹ and from 0.1 to 0.62 m s⁻¹.

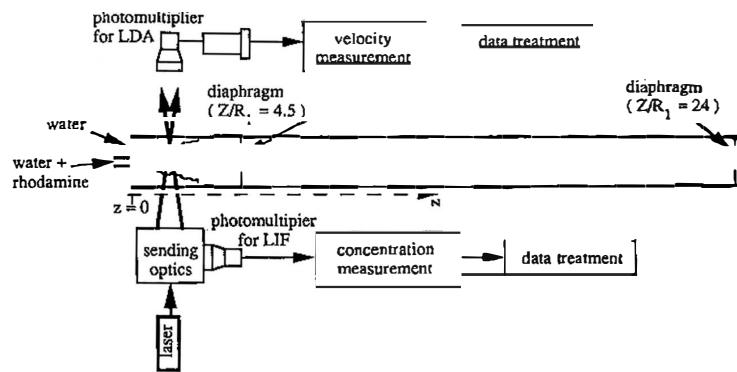


Figure 1. Experimental equipment.

Jet Directed onto a Diaphragm

Within the main tube of the reactor is stuck a PVC diaphragm of thickness 5×10^{-3} m. Several cases are checked, using two diaphragms:

- (1) the largest diaphragm (inner radius $R = 1.5 \times 10^{-2}$ m) is tested at $Z = 4.5 R_1$. Knowing the general hydrodynamical structure of a confined jet⁸, it seems that the jet can probably impinge onto such a large obstacle. The drag behind the diaphragm though may produce some additional turbulence⁹. However, three other positions are also tested: $Z = 4.5 R_1$, $Z = 24 R_1$, $Z = 45 R_1$ and $Z = 68 R_1$.
- (2) the second diaphragm is tighter ($R = 10^{-2}$ m) and settled at $Z = 4.5 R_1$ to possibly break the turbulent jet surrounding zone.

Swirling Jet

To create the swirl effect of the jet, a twisted tape is placed inside the nozzle (thickness is 10^{-3} m and length 11.10^{-2} m). The tape ends 10^{-2} m before the nozzle extremity so that the central flow disturbance due to the tape vanishes. Three tapes are used in this work; their respective threads are $pa = 0.1$ m, $pa = 0.05$ m and $pa = 0.04$ m. Velocity measurements at the jet's exit enable the calculation of the respective swirl numbers: $S = 0.17$, $S = 0.31$ and $S = 0.41$, where¹⁰:

$$S = \frac{2\pi \int_0^{R_0} r \overline{U(r)} \overline{W(r)} r^2 dr}{2\pi R_0 \int_0^{R_0} r \overline{U(r)}^2 r dr}$$

$U(r)$ and $W(r)$ are respectively the mean axial and tangential velocities at radial position r .

Study Parameters

The dimensional analysis of the two considered cases¹¹ put the following non-dimensional parameters in evidence: the Reynolds number related to the jet Re ; the inlet velocity ratio U_0/U_1 ; the swirl number S in the case of the swirling jet; in the case of the diaphragm the non-dimensional inner radius R/R_1 and its axial position Z/R_1 .

Experimental variation ranges for these parameters are shown in Table 1.

Table 1.

Diaphragm	Swirl
U_0/U_1 : 17.4 to 53.3	U_0/U_1 : 3 to 80
Re : 53,000 to 137,000	Re : 3000 to 137,000
Z/R_1 : 4.5 to 68	S : 0.17, 0.31 and 0.41
R/R_1 : 0.4 to 0.6	

EXPERIMENTAL TECHNIQUES

Two methods are successively used: a global approach, to oversee the behaviour of each configuration, and then a local approach to detail and confirm the first conclusions.

The two approaches for mixing investigation use the phenomenon of laser induced fluorescence. A fluorescent tracer (rhodamine B) is continuously introduced in the jet flow only. This tracer, when illuminated under a proper wave length, emits a specific fluorescent light and puts in evidence the mixing behaviour of the reactor. The incident illumination is created by a SPECTRA-PHYSICS 164-06 Argon laser running on the blue ray (488 nm) and with a power of about 0.5 W.

Global Approach

It is possible to light a whole plane of the reactor by spreading the laser ray into a sheet—for instance by refracting it on a glass cylinder¹². In this study the longitudinal plane of symmetry of the reactor is investigated. More or less fluorescent zones appear in this plane; they reveal the local concentration of rhodamine B. The axial distance needed to reach apparent mixing ('mixing length' L_m : axial distance at which fluorescence seems uniform on a whole section) is measured, for every configuration, on photographs of the illuminated plane (Figure 2). To obtain a better contrast, photographs are taken in darkness with black and white KODAK TRI-X PAN 400 ASA films.

Local Approach: LDA and LIF

The local approach concerns both hydrodynamics and mixing description. Local velocity measurements are

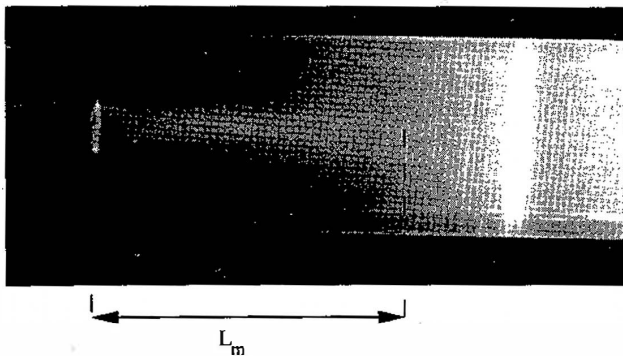


Figure 2. Photograph of a laser sheet enlightened plane of symmetry inside the reactor, showing mixing zone.

performed by a laser Doppler velocimeter (DANTEC), coupled to the above cited laser (Figure 1). Treatment of the measurements is performed on a personal computer: mean values and mean quadratic fluctuations of axial, radial and tangential velocities are calculated from raw measurements.

The local concentration measurements are performed by the Laser Induced Fluorescence technique: within a probe volume, defined by the laser rays crossing volume, fluorescence intensity is measured by the means of a photomultiplier. This intensity is proportional to the local concentration of the fluorescent tracer. A complete description of the LIF apparatus can be found in a former article⁸.

GLOBAL INVESTIGATION OF THE TUBULAR REACTOR CONFIGURATIONS

Comparisons of the Apparent Mixing Lengths

Figure 3 shows values of L_m/R_1 measured at $Re = 53,000$ under various ratios U_0/U_1 . It can be observed that L_m/R_1 is always shorter in the case of the swirling jet than in the reference case of classical jet. Even at the lowest swirl number of this study ($S=0.17$), the swirl effect reduces L_m/R_1 of more than 15% in comparison with the reference case ($S=0$). This proves the expected effectiveness of swirling jet.

In the case of diaphragms, however, L_m/R_1 is always longer than the reference value; it is even twice this value for $U_0/U_1 = 26.7$ and $R/R_1 = 0.6$. Diaphragms seem to slow mixing.

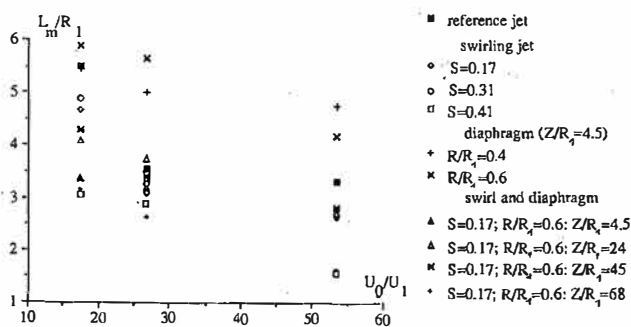


Figure 3. Mixing lengths for different U_0/U_1 .

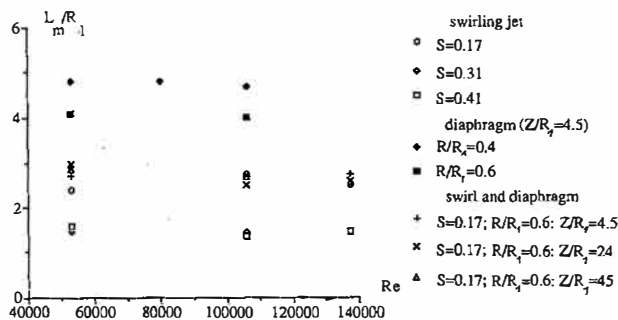


Figure 4. Influence of Re on mixing length under turbulent regime.

Influence of Parameters

Influence of inlet speed ratio U_0/U_1

Figure 3 ($Re = 53,000$) indicates that L_m/R_1 decreases when U_0/U_1 increases.

Influence of Re

Figure 4 presents curves of L_m/R_1 versus Re under constant U_0/U_1 ($U_0/U_1 = 53.3$), where Re varies from 53,000 to 137,000. These curves show very little influence of Re in this range of variation.

Re is not a significant parameter for the effectiveness of turbulent mixing in that range. This conclusion has already been reached for other mixers^{13,14}, but experiments at smaller Re (from 3000 to 21,000) point to the same conclusion¹¹.

Jet directed onto a diaphragm: influence of Z/R_1

No influence of Z/R_1 is noticed, whatever U_0/U_1 (Figure 3). Furthermore, when Z/R_1 equals 4.5, mixing is slowed down.

Jet directed onto a diaphragm: influence of R/R_1

Each diaphragm ($R/R_1 = 0.4$ and 0.6) gives similar results for $Z/R_1 = 4.5$, whatever U_0/U_1 (Figure 3). These diaphragms are not able to develop any additional turbulence in the reactor.

Swirling jet: influence of swirl number S

Figures 3 and 4 show that the higher S is, the shorter L_m/R_1 is.

Conclusion

This global analysis reveals that the introduction in the reactor of a diaphragm whose ratio R/R_1 is more than 0.4 is of no interest. This fact is certainly due to the contraction of the flow inside the diaphragm¹¹, leading to a decrease of the turbulence level whereas an increase was expected. To improve mixing in the axisymmetrical jet reactor, one has then to put this idea to one side and to develop that of the swirling jet, which seems to be promising. A local study of this case is now performed, to verify and explain its performance.

LOCAL INVESTIGATION OF THE SWIRLING JET REACTOR

A detailed investigation has been realized at $Re = 40,000$, $U_0/U_1 = 17.4$ and $S = 0.31$. A precise report of this

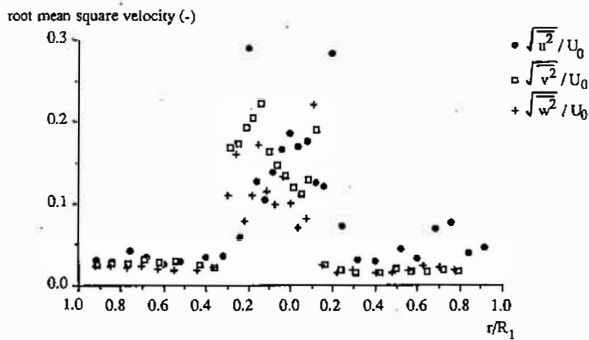


Figure 5. Root mean square velocities at $z/R_1 = 0.08$.

investigation has been published elsewhere¹⁵. Mean velocities and their fluctuations throughout the reactor have first been measured to describe the flow structure. The mean concentration and its fluctuations have been evaluated to analyse the mixing process.

Hydrodynamics of the Swirling Jet Reactor

The twisted tape creates mean tangential velocities \bar{W} within the jet¹⁵, which generate additional turbulence all around the jet, as explained earlier. This specific turbulence appears through high root mean square velocities $\sqrt{u^2}$, $\sqrt{v^2}$ and $\sqrt{w^2}$ (Figure 5) and makes the swirling jet expand more rapidly into its co-current than the corresponding non-swirling jet¹⁰: homogenization of \bar{U} happens faster.

Mixing in the Swirling Jet Reactor

Swirling jet eddies should provide active mixing, as expected in the literature⁶. Root mean square concentrations, normalized by the mean local concentration \bar{C} , reveal the local state of homogenization. This segregation intensity I_s is drawn along the axis of the reactor on Figure 6. It reaches a higher peak in the swirling jet cases than in its non-swirling reference; I_s vanishes earlier too on the reactor axis, proving the greater effectiveness and speed of mixing of the swirling jet.

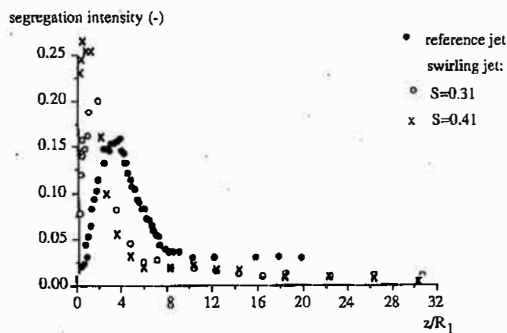


Figure 6. Segregation intensity along the reactor axis.

Conclusion

The local analysis of velocities and concentrations through the reactor agrees with the results of the global approach: the swirl of jet is a turbulence promoter and it speeds mixing up.

The benefit in mixing rate due to the swirling jet has to be tested in a real industrial reactor in terms of reactant conversion.

TEST ON INDUSTRIAL SITE

A twisted tape was placed in a reactor nozzle for a unit which usually produces some 200,000 t/year of ammonium nitrate. The $z=0$ expected swirl number, based on the tape's thread and the feed flow rates, is of $S = 0.17$ ¹¹.

Thanks to this twisted tape, the waste ammonia—usually some 4% of feed ammonia—is halved. Better performances are expected by increasing the swirl number of the jet.

During the experiments, realized under 400,000 Pa, no significant pressure loss increase has been noticed, the measurement precision being of 10,000 Pa.

The method tried for the analysis of the tubular reactor has been successful. Elf-Atochem has thus licensed the new reactor structure¹⁶.

CONCLUSION

To analyse the behaviour of an axisymmetrical jet-stirred reactor, a specific approach has been tested: a theoretical study on turbulent mixing and its promotion has put in evidence the possibility of some modifications to improve the reactor performance. Then a global analysis, performed on an experimental plant by an optical technique, showed the effectiveness of swirling jet. A swirling jet configuration of the reactor has been investigated locally by the means of velocity and concentration measurements: this third step has confirmed the conclusions of the global approach. The swirling jet solution has then been adopted and tested on industrial site: this configuration has resulted in a halving of the amount of waste ammonia.

The study has also shown that mixing is all the more rapid as inlet speed ratio and swirl number are high. Tests on industrial site of more intense swirls would be of great interest: still fewer ammonia wastes can be hoped for.

NOMENCLATURE

I_s	segregation intensity
L_m	apparent mixing length, m
pa	thread of twisted tape, m
r	radial coordinate, m
R	inner radius of diaphragm, m
R_0	radius of nozzle, m
R_1	radius of reactor, m
Re	Reynolds number relative to the jet
S	swirl number
$\sqrt{u^2}$	root mean square axial velocity, $m\ s^{-1}$
\bar{U}	mean axial velocity, $m\ s^{-1}$
U_0	mean inlet velocity of jet, $m\ s^{-1}$
U_1	mean inlet velocity of co-current, $m\ s^{-1}$
$\sqrt{v^2}$	root mean square radial velocity, $m\ s^{-1}$

\bar{V}	mean radial velocity, m s^{-1}
$\sqrt{w^2}$	root mean square tangential velocity, m s^{-1}
\bar{W}	mean tangential velocity, m s^{-1}
z	axial coordinate, m
Z	axial position of diaphragm, m

Greek letters

ρ	density, kg m^{-3}
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ADDRESS

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