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Abstract: An original gas-liquid contacting system is proposed, consisting of a pump, an orifice, a vertical tube coaxial to the orifice and an impinging plate. The pump generates a downward vertical liquid jet through the orifice situated above the gas-liquid dispersion level. The two phase jet is directed towards an impinging plate near the bottom of the tank and dispersed in the volume of the liquid. Liquid is withdrawn below the impinging plate and recycled. This reactor may be used for gas-liquid reactions (*ie* hydrogenations) and also to mix liquids, to disperse particles, to oxygenate waste water etc…. Performances and design rules of this equipment are proposed. Then, the results are compared to performances of bubble columns, stirred tanks, and other academic and industrial jet systems. It is shown that, at a given energy dissipation, this system yields much higher mass transfer densities than a classical stirred tank provided with a Rushton turbine. Finally some suggestions about mass transfer mechanisms and efficiency of dissipated power are given.

Keywords: Gas-liquid reactors, impinging jet, energy efficiency, bubble columns, stirred tank.

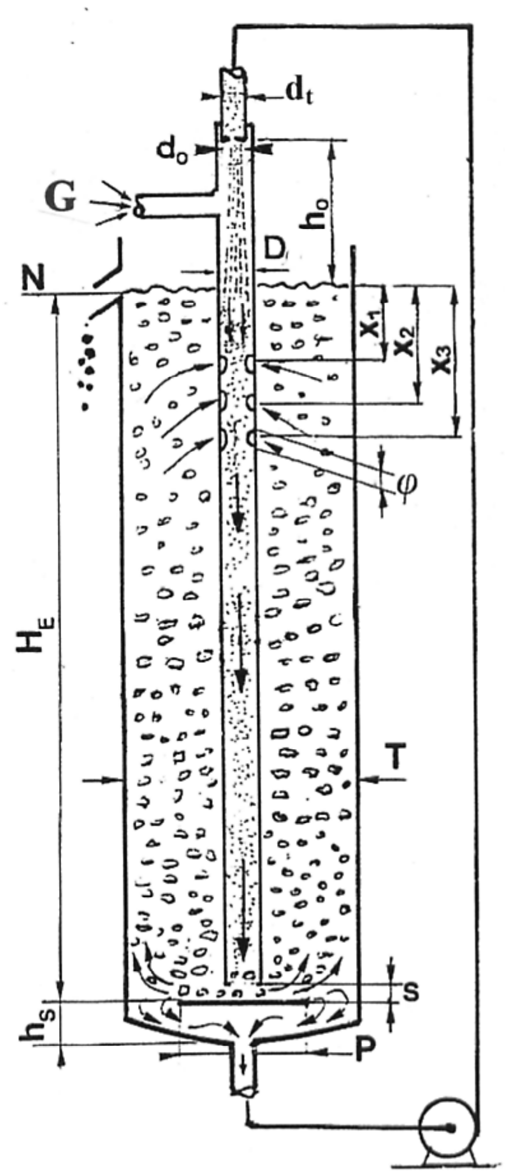
1. INTRODUCTION

Chemical and biochemical industries need simple high performance gas-liquid systems to achieve high productivity and selectivity reactors. The purpose of this article is to propose a very simple reactor achieving this goal. It consists only of an orifice, a tube, a plate and a pump. In the present system, mechanical energy is provided by the liquid pump exclusively, while in bubble columns it is provided by the gas compressor, and in stirred tank reactors by the stirrer engine and the gas compressor. The aim of this article is to provide simple and reliable design rules for the jet device presented here, and to compare the energy efficiency in terms of k_La values with that of other devices.

2. EXPERIMENTAL SET-UP AND OPERATING CONDITIONS

2.1 Description of the impinging jet device used here.

Fig.1 shows an example of an experimental set-up. It consists of a tank, a pump, a nozzle with an orifice diameter $\mathbf{d_o}$, a perforated tube **D (**coaxial to the orifice) above and below the dispersion surface, and of an impinging plate **P**. The gas is introduced in the tank by the top. It is entrained downwards in tube **D** by the liquid jet provided by the nozzle; further gas and gas-liquid mixture is sucked in through the holes in the wall of **D** and is entrained downwards. The gas-liquid jet is then carried through tube **D** and impinges on plate **P**; the impact causes the gas to be dispersed in the whole the tank. Above the plate, the dispersion of bubbles has a uniform aspect, while below the plate, with an appropriate design, no bubbles are observed. The liquid is recycled from below the plate through the pump. The dimensions indicated in Fig. 1 correspond to optimal results according to experiments made in industrial scale equipment.



T mm	250	480
H_E mm	850	2350
h_s mm	100	200
h_o mm	<200	
d_o mm	12	24
D mm	33	57
S mm	20	30
P mm	120	240
φ mm	16	27
X_1 mm	130	225
X_2	190	325
X_3	250	430
N_t	3X2	
d_t mm	25	50

Fig. 1. Description of an optimized gas-liquid impinging jet system

If necessary, several tanks can be used to obtain the gas and liquid flow rates needed by the reaction. If, for safety reasons (e.g. hydrogenations), the exit of liquid at the bottom of tank is not wanted, it is possible to place it at the top, using a tube parallel or coaxial to tube **D** and the nozzle $\mathbf{d_0}$. The advantages, compared with a stirred tank are the absence of moving parts (eliminating sealing problems) and the possibility, if a heat exchanger is required, to install it outside of the tank on the liquid recycling line.

2.2 Operating conditions and measuring techniques using the impinging jet device.

The gas used in the experiments was air at room temperature and pressure, the liquid was either tap water or a water-sulfite solution in case of mass transfer or interfacial area measurements.

Several jet systems were tested with air and water using a nozzle diameter of d_o=0.010m and tanks of diameters T=0.25 and 0.48m where dispersion levels were adjusted by overflow. Tests have consisted of measuring the total bubble volume and mass transfer rate generated by a given energy input. In the case of a coalescing gas-liquid system, under the conditions investigated, no gas entrainment below the plate was observed, so that an effective recycle of the liquid was possible.

The effect of the orifice diameter, (always with air and water) was investigated using the following two plants. The first one, with a nozzle orifice diameter d_o=0.012m, was called "optimized system N°1" and the second, with d_o=0.024m, "optimized system N°2". The other dimensions are those indicated in Fig. 1.

During all these studies, the following variables were generally tested: jet velocity V_o (4 to 12 m.s^{-1}), nozzle orifice diameter d_o (0.009, 0.010, 0.012, 0.024 m), tube diameter D (0.025, 0.033, 0.045, 0,057, 0.067 m with or without immersed holes to recycle dispersion), tank diameter T (0.25, 0.48 m), dispersion height H_E fixed by overflow (0.5, 0.85, 1.85, 2.35 m). Some experiments were made with a sodium sulfite solution to investigate the effect of a coalescence inhibiting system and to determine the volumetric mass transfer coefficient k_La or the gas-liquid interfacial area by the chemical technique.

The measuring techniques are quite classical: the gas volume in the tank was determined by stopping the liquid flow and by measuring the liquid level before and after gassing. The liquid flow rate was determined using a rotameter, the induced gas flow rate by a Pitot tube at the gas entrance and the pressure in the nozzle by a manometer. The global liquid side mass transfer capacity Q_T ($Q_T = k_L a_E V_{E,} = k_L a_L V_L$) ($m^3.s^{-1}$) was determined by using the classical dynamic reoxygenation technique or by the slow oxidation of sufite reaction technique. The interfacial area by using the pseudo-mth order rapid reaction technique (oxidation of sulfite catalyzed by cobalt sulfate).

2.3 Experimental results

Contrarily to the classical gas-liquid mixed tanks and bubble columns, the induced gas flowrate depends on the liquid velocity at the outlet of the nozzle (*ie* the liquid flowrate and orifice diameter d_o of the nozzle). Only some hydrodynamics and mass transfer results obtained with the optimized reactors will be presented here. The effect of operating conditions on hydrodynamic (ie gas induced flow rate and gas holdup) and mass transfer parameters (interfacial area and volumetric liquid side mass transfer k_La) has been studied in order to establish correlations between design parameters and operating conditions for design purpose.

<u>Hydrodynamic parameters :</u>
The effect of the liquid velocity at the nozzle outlet on the induced gas flowrate Q_G obtained with both (N°1 and N°2) optimized jet impinging reactors is represented on figure 2. One can observe the logical increase of Q_G with V_o due to the decrease of pressure as V_o increases at the outlet of the nozzle. Furthermore, no effect of reactor geometry is obtained, which is probably due to the fact that the optimized reactors are almost geometrically similar. The evolution of the gas holdup with V_o (figure not shown) is similar to that of Q_G.

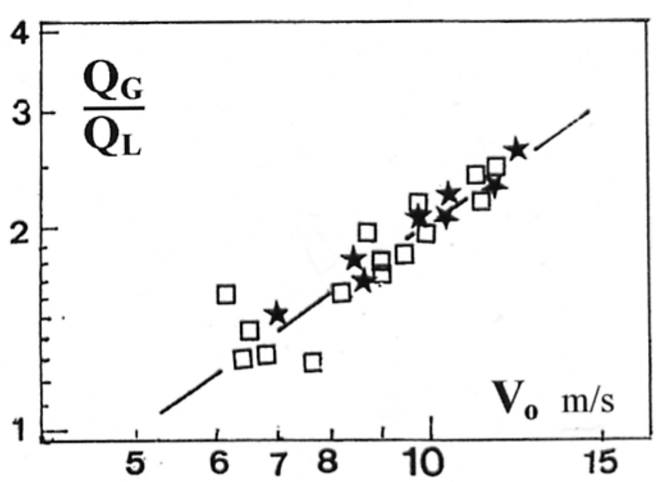


Fig.2. Gas rate induced by the liquid jet for both optimized reactors :N°1 (d_o=12 mm): open symbols; N°2 (d_o=24 mm) black symbols. Results obtained with Air/water system.

<u>Mass transfer parameters:</u>
Results of the volumetric gas-liquid mass transfer coefficient $k_La = Q_T/V_L$ obtained from the dynamic method using air/water system are reported on figure 3 as a function of the gas to the liquid volume ratio. As expected, considering the increase of the gas induced flowrate and the gas holdup with the liquid velocity V_o at the nozzle outlet, the values of k_La also increase with V_B/V_L regardless of the geometry of the optimized impinging jet reactor as in the case of the gas induced flow rate results shown before.

Other results of k_La have also been obtained for different emulsion heights and from the slow sulfite oxidation reaction technique. The volumetric mass transfer coefficient k_La generally increases with a decrease of the emulsion height due to a the increase of the gas induced flowrate. In presence of coalescence inhibiting system which is the case of the air/sulfite system, k_La values are much higher than in presence of air/water system due to higher gas suction rates and gas holdups (not represented here). This result is commonly reported in literature for other types of gas-liquid reactors (stirred tanks, bubble columns etc…).

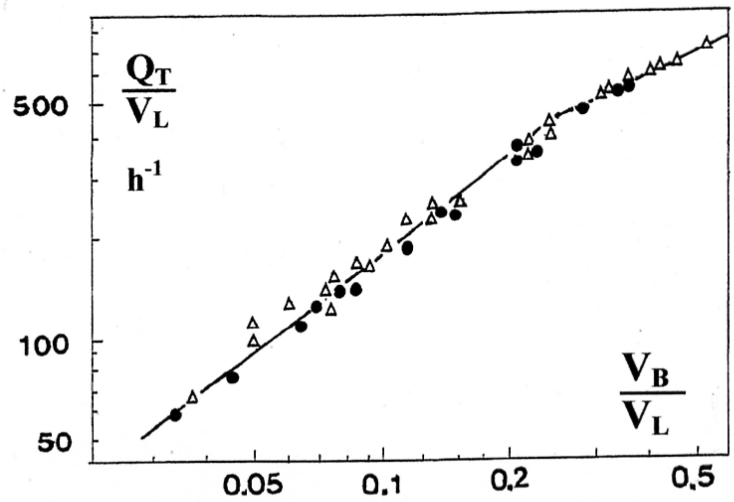
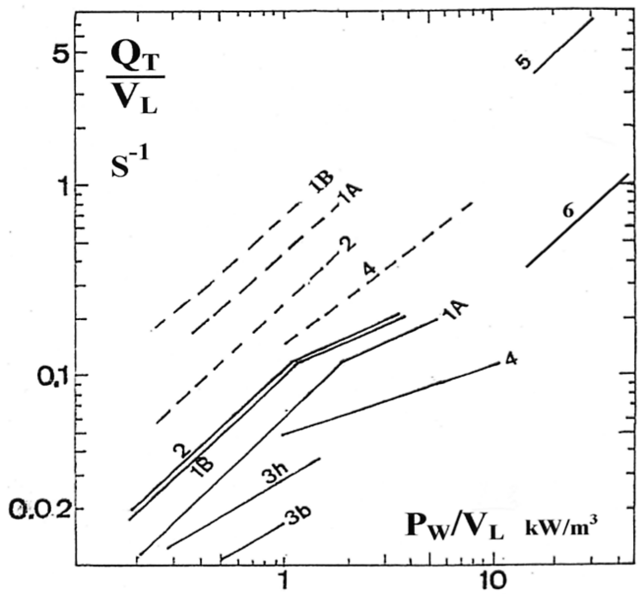


Fig. 3. Evolution of k_La (= Q_T/V_L) with the gas to liquid volume ratio for both optimized reactors: N°1 (d_o=12 mm): open symbols; N°2 (d_o=24 mm): black symbols. *Air/ water system.*

<u>*Comparison of the impinging jet reactor with other classical reactors:*</u>

Hydrodynamic and mass transfer experiments have also been conducted in bubble columns and in stirred tanks provided with a Rushton turbine in order to compare k_La values at a given specific dissipated power. The chosen reactors had quite similar heights and diameters as those of the impinging jet reactors.



<u>Fig. 4.</u> Liquid-side mass transfer versus specific dissipated power. Continuous lines: air/water system; doted lines: air/sodium sulphite solution; (1A, 1B) .Studied impinging reactors for power at entrance and exit of orifice; (2) Bubble columns (This work); (3h, 3b) Plume dispersions with down and up aerated jets. Tojo *et al* (1982); (4) Mechanically stirred tanks Van 't Riet (1983), Midoux (1978), Botton et al. (1980)*;* (5) Impingement of two aerated jets. Gaddis (1994); (6) Plume dispersion confined into a tube. Evans *et al* (2001)

The volumetric gas-liquid mass transfer coefficients (k_La = Q_T/V_L) obtained with the impinging jet reactor was finally compared to those determined in the studied bubble columns and stirred tanks and also to those published for other reactor geometries. For this purpose, k_La values have been represented in figure 4 as a function of the specific power input P_W/V_L. Figure 4 shows that the impinging jet system is more efficient than bubble columns and stirred tanks for coalescence inhibiting liquids. For coalescent liquids, it is more efficient than the classical gas-liquid stirred tanks provided with a Rushton turbine and avoids the sealing problems commonly encountered in stirred tanks; it is almost as efficient as bubble columns but easier to scale up and to simulate than bubble columns. Also indicated are values obtained with different other contacting devices: higher volumetric mass transfer coefficients can be achieved (e.g. by the impingement of two aerated jets, Gaddis, 1994), but at the expense of higher mechanical energy dissipation.

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