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Chemical Engineering Science 60 (2005) 6378 – 6390

Chemical Engineering Science

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Using in-line static mixers to intensify gas–liquid mass transfer processes

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Received 25 November 2004; received in revised form 1 March 2005; accepted 3 March 2005

Abstract

A novel static mixer design (screen-type elements) capable of taking advantage of the interfacial characteristics of industrial gas/liquid systems was developed. The interfacial area of contact, and volumetric oxygen transfer coefficient, were investigated using a 25.4 mm pipe loop in which liquid superficial velocities of up to 2.0 m/s (and gas holdups as high as 0.15) were tested. Volumetric mass transfer coefficients as high as 0.44 s^{-1} were achieved. The ability of this design to achieve high energy utilization efficiencies is validated by achieving oxygen transfer rate as high as 4.2 kg/kWh in the presence of surfactants.

Depending on the process requirements and the interfacial properties of the system, high volumetric oxygen transfer coefficients or high energy utilization efficiencies can be achieved by modifying the contactor design and/or operating conditions.

Keywords: Process intensification; Gas–liquid contacting; Mass transfer; Surface active agents; Industrial streams; Static mixers; Screen; Energy utilization; Bubbles; Coalescence

1. Introduction

Process intensification is a relatively new concept that has been gaining strong momentum because of its ability to significantly reduce capital and operating costs while improving process yield/selectivity and enhancing the inherent safety of many CPI operations (Stankiewicz and Moulijn, 2002). Such desirable benefits are mainly based on the ability to match the fluid dynamics of mixing to the chemical, biological and/or physical requirements of the process. This investigation, which focuses on enhancing inter-phase mass transfer between gases and industrial liquids, provides an example of such a situation.

The approach presented in this investigation is based on the fact that most industrial liquids contain varying quantities of secondary compounds (alcohols, organic acids, electrolytes, amines, glycols, proteins, finely divided particles and emulsions) the presence of which is known to strongly affect the hydrodynamics of gas/liquid contacting. They also adversely impact the volumetric inter-phase mass transfer coefficient [$k_L a$] in a fashion that is dependent on the type and concentration of the contaminant, as well as the type of gas/liquid contactor used (Jamialahmadi and Muller-Steinhagen, 1992; Shen et al., 1999; Al-Masry, 1999; Vazquez et al., 2000a; Vasconcelos et al., 2002). This observation is mainly attributed to the reduction of the liquid phase mass transfer coefficient due to the presence of contaminant at the interface. On the other hand, the presence of these contaminants can significantly reduce bubble coalescence rate (Camarasda et al., 1999; Zahradnik et al., 1999), a phenomenon that can be taken advantage of to achieve large interfacial area of contact at low energy consumption rates.

The effect of contaminants on the gas/liquid behaviour of industrial streams can be attributed to the observation that the bi-polar contaminant entities tend to adsorb at the interface and depict interfacial characteristics that are very similar to those of dilute surfactant-containing aqueous solutions (Al Taweel et al., 2005), including the development of Marangoni elastic interfacial forces. When the bubbles move relative to the surrounding liquid, the surface active contaminant entities get convected to the bubble's tailing end where they accumulate forming a stagnant cap. This reduces internal circulation and the value of the inter-phase mass

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0009-2509/$ - see front matter © 2005 Published by Elsevier Ltd.
doi:10.1016/j.ces.2005.03.011

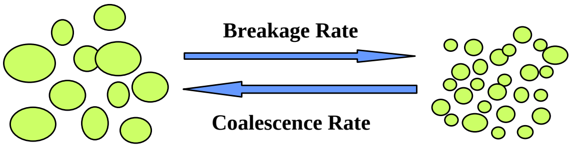

Fig. 1. Dynamic equilibrium between bubble breakage and coalescence processes.

transfer coefficient, k_L, decreases from that of a circulating bubble (Higbie's penetration theory) to that of a rigid sphere (Frössling equation). This represents up to 7-fold reduction in the case of 1 mm bubbles (Bischof et al., 1993; Vasconcelos et al., 2002; Vazquez et al., 2000a; Alves et al., 2004). Additional reduction is caused by the ability of the Marangoni elasticity to dampen the hydrodynamic disturbances near the gas–liquid interface (Kastánek et al., 1993; Walter and Blanch, 1986; Vazquez et al., 1997, 2000a,b; Shen et al., 1999), a factor that plays an important role in determining the magnitude of inter-phase mass transfer (Davies, 1972).

In order to understand the effect of surface active agents, SAA, on bubble breakage and coalescence, it is necessary to consider their effect on the counteraction processes of bubble dispersion and coalescence (Fig. 1), an approach which forms the basis of the widely used population balance analysis. The presence of surface active contaminants in industrial gas/liquid systems (or systems in which trace concentrations of SAA are present e.g., industrial and municipal wastewaters) strongly affects the rate of bubble coalescence as well as the rate of bubble breakage and, thereby, influences the size distribution of the bubbles present in the gas/liquid contactor. Walter and Blanch (1986) found that the presence of SAA in low concentrations increases the maximum stable bubble size, a phenomenon that was attributed to the ability of the Marangoni elastic forces to resist the surface stretching encountered during bubble breakup. On the other hand, the ability of SAA to retard bubble coalescence is much more pronounced and order of magnitude reductions in coalescence rates have been observed at very low surfactant concentrations (Machon et al., 1997; Luo, 2002).

A novel static mixer design (screen-type static mixers) that is capable of taking advantage of the aforementioned phenomenon was developed. It has been successfully used to generate narrowly-sized liquid–liquid dispersions in an energy efficient fashion (Al Taweel and Chen, 1996; Al Taweel et al., 2003). When used in conjunction with gas–liquid systems, interfacial area of contact as high as 2200 m^2/m^3 were obtained in the regions adjacent to the screens where local energy dissipation rate is highest (Chen, 1995). The fine bubbles formed in these regions tend to coalesce as they migrate to regions of lower energy dissipation rates (further downstream) and the coalescence hindrance phenomenon encountered in industrial streams is taken advantage of to maintain high interfacial area of contact for relatively longer times. The formation of such high interfacial area of contact is expected to enhance inter-phase mass transfer particularly considering the very intense micro mixing levels encountered in the regions close to the screens.

The objective of this investigation is to determine the operational characteristics of this novel gas–liquid contactor and to establish how the volumetric mass transfer coefficient is affected by the interfacial characteristics of the system.

2. Experimental

In this investigation, small quantities of surface active agents (SAA) were added to the aqueous phase in order to simulate the behaviour of industrial streams (Al Taweel et al., 2005) as well as wastewaters in which SAA are present (Stenstrom and Gilbert, 1981; Wagner and Popel, 1996). Consequently, a physical technique for measuring volumetric mass transfer (oxygen desorption method) was selected in order to eliminate the influence of the reagents needed for the various chemical techniques.

The continuous flow experimental setup used in this investigation is schematically depicted in Fig. 2. The aqueous phase was prepared and stored in a 1000 L agitated tank. The oxygen content of the aqueous phase was raised to 9–10 ppm by bubbling air through a sintered sparger for a period of about 2 h. The aqueous phase was fed to the static mixer loop using a variable speed centrifugal pump (MONARCH Industries, Model ACE-S20) and its flow rate measured using a paddle flow meter (SIGNET model: MK 309). The liquid flow rate was manually varied from 0.253 to 1.26 L/s which yielded superficial liquid velocities in the pipe ranging from 0.5 to 2.5 m/s.

Gas liquid contacting was conducted in a 5.12 m long horizontal pipeline constructed using transparent polycarbonate tubing (25.4 mm ID). The pipeline was built from flanged sections to enable the placement of screen mixing elements at different positions. Most of the experiments were carried out using a single screen, but few runs were conducted to evaluate the effect of adding a second screen (placed 370, 775 and 1175 mm downstream from the first) on the overall mass transfer coefficient. The characteristics of the stainless steel plain-weave wire cloth screens used in this investigation are given in Table 1. The individual jet diameters, d_{jet}, listed in Table 1 were defined as the diameter equivalent to the round-shaped jet with the same opening area,

$$d_{\text{jet}} = \sqrt{4(M-b)^2/\pi}. \qquad (1)$$

Screen-type static mixing elements were used in this investigation because of their ability to generate reasonably uniform hydrodynamic conditions across the cross-sectional area of the pipe and their ability to efficiently generate liquid dispersions (Al Taweel and Chen, 1996).

It is well known that the local value of the energy dissipation rate, ε, downstream from screens undergoes dramatic variation along the axis of flow with the maximum value being encountered in the immediate vicinity of the screen