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Hydrodynamic and mass transfer performance of a new aero-ejector with its application to VOC abatement

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Abstract

The aero-ejector, an in-house developed gas–liquid contactor, ensures an improved gas–liquid contact, favorable to a high mass transfer in a small volume: its transfer capacity enables the elimination of 90% of pollutants from gaseous effluents in a single treatment. Through its characteristics, its use as a transfer device into a treatment process has distinct advantages. However, such an application needs modifications to make the contactor suitable for use in an industrial context (efficiency, compactness and low pressure drop). The aim of this research is to improve the contactor geometry in order to enhance its performances. Modifications have resulted in an energy improvement since an inlet gaseous pressure of 0.05×10^5 Pa was reached for a Q_G/Q_L ratio in excess of 10 and with a small loss of transfer efficiency. The study of the effect of operating parameters has identified a sizing criterion, the "useful volume". This can be used to determine an optimal configuration for the gas–liquid contactor taking into account constraints such as pollutant solubility, pressure drop or compactness.

Keywords: VOC; Gas–liquid contactor; Absorption; Mass transfer; Hydrodynamics; Fluid mechanics

1. Introduction

The treatment of waste gas containing volatile organic compounds (VOCs) is a major environmental problem for such industries as refineries, transport, incineration, painting and surface treatment. Nowadays, numerous treatment processes are available and can ensure satisfactory purification rates, e.g. incineration, cryogenics, adsorption, scrubbing, biofiltration, membrane separation or the foamed emulsion bioreactor (Everaert and Baeyens, 2004; Everaert et al., 2002, 2003; Kan and Deshusses, 2003; Kennes and Veiga, 2004; Iranpour et al., 2005; Van Groenestijn and Kraakman, 2005). The most widely used processes still are incineration or adsorption representing at least 70% of gas treatment installations in Europe and the United States (Dueso and Lambert, 1997). However, the application domain of these two technologies is not universal (Ademe, 1997; Ceccaldi et al., 1993; Le Cloirec, 1998; Siegell, 1996). Costs induced by the use of an efficient process which is poorly adapted to emission characteristics constitute a limitation to the development of an environmental strategy for gaseous emissions. Emission purification often encounters the problem of treating large gas flow rates (from 10^3 to 2×10^5 $m^3 h^{-1}$) polluted with low VOC concentrations (from 0.1×10^{-3} to 10^{-2} $kg m^{-3}$). Because of high gas flow rates, large processing units are needed to reach a satisfactory treatment efficiency. One solution can be the optimization of the gas–liquid mass transfer step to reduce the treatment unit size. A gas–liquid contactor, developed in our laboratory and called "aero-ejector" (De Billerbeck and Fonade, 1996), can be used as the pollutant transfer device from the gas to the liquid phase with the aim of either concentrating the gaseous effluent (in association with a desorption step) or developing a destructive treatment solution (in association with a biological reactor).

The hydrodynamic and mass transfer characteristics of the aero-ejector have already been reported (De Billerbeck and Fonade, 1996; Rainer et al., 1995). They drew attention to the contactor efficiency with model molecules such as oxygen and ethanol: for instance, a 90% elimination was obtained with a

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single treatment of the gaseous phase (Daubert et al., 2001). However, taking the industrial conditions into account, the main disadvantage was identified as too high a gas pressure, leading to the use of a costly rotary blower (De Billerbeck et al., 1999). The present study deals with an optimization of this contactor in order to make it suitable for industrial applications (improvement of transfer performances and minimization of energy consumption). Usually, industrial constraints are an inlet gaseous pressure below 5×10^3 Pa for a Q_G/Q_L ratio in excess of 10.

1.1. The aero-ejector

Its internal geometry has been deduced from that of the hydro-ejector used for bioreactor aeration (Rainer et al., 1995). It is composed of two parts: the inlet cone and the outlet dispersion zone (Fig. 1). This apparatus enables a liquid phase to be swept along by a gas flow: the existence of a vena contracta induces a negative pressure, which provokes liquid suction. Nevertheless, because of the difference between the volumetric masses of the two phases, a pump is necessary to ensure a satisfactory liquid flow rate. After suction, the liquid phase probably forms a film along the pipe wall. Theoretical calculations demonstrated that the re-attachment of the stream behind the sudden internal contraction happens in section S_1 (Fig. 1) (De Billerbeck and Fonade, 1996). The hydrodynamic perturbations provoked by the internal geometry create a two-phase flow and liquid phase dispersion ensures an efficient mass transfer.

From these results, this contactor appears to be a satisfactory way to transfer pollutants from the gas to the liquid phase. Its small size and flexibility combined with good transfer performances make it useful as part of treatment processes of gaseous emissions with low VOCs concentrations (Daubert et al., 2001). Thus, the aero-ejector is actually used as a transfer device in a process which aim is to concentrate gaseous VOC. Pollutants are first transferred into the liquid phase and desorbed from the liquid phase into a smaller gas flow rate. Concentrated pollutants retrieved at the gaseous process outlet can be either recycled in the case of compounds of interest or degraded using the appropriate treatment in a cost-effective way (Fig. 2).

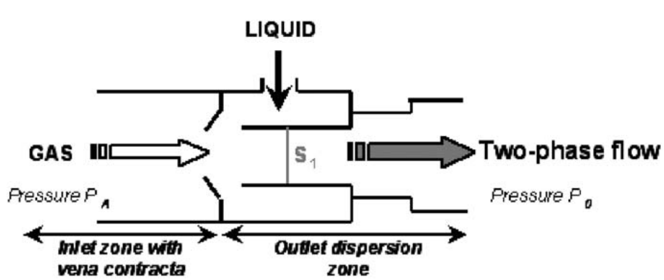

Fig. 1. Simplified diagram of the aero-ejector.

2. Experimental

2.1. Volatile organic compounds

During this study, we used three target pollutants, frequently encountered in industrial gaseous emissions (as for example in printing or in pharmaceutical industries): ethanol (EtOH), methyl ethyl ketone (MEK) and butyl acetate (BA). Added to their non-toxicity and their processing facility, the major interest of these molecules is their difference in solubility in water, which enables us to test process efficiency in different cases. Henry's constant was reported for EtOH, MEK and BA (respectively 0.3×10^5, 3.9×10^5 and 17.9×10^5 Pa (Sander, 1997).

The main air stream was saturated with water vapour by sparging the air through a 20 L tank containing tap water. Three smaller compressed air streams were sparged in a 1 L bottle, hermetically closed, containing liquid VOC (EtOH, MEK or BA as required) and subsequently mixed with the main humidified air stream. Three scales (Sartorius EA6DCE1, accuracy 0.2×10^{-3} kg) allowed the mass flow rate of entrained VOCs to be measured. The streams were measured with float flowmeters (main air stream: Krohne, 20 °C, 1.0132×10^5 Pa, range (1.4×10^{-4}–1.4×10^{-3} $m^3 s^{-1}$ for the smaller main flow air streams: Krohne, 20 °C, 1.0132×10^5 Pa, butyl acetate: range 0.17×10^{-3}–1.7×10^{-3} $m^3 s^{-1}$; ethanol and methyl ethyl ketone: range 5×10^{-5}–5×10^{-4} $m^3 s^{-1}$)). VOC concentrations were calculated dividing mass flow rates by streams.

2.2. Experimental set-up for absorption experiments

The entire contactor is composed of an aero-ejector and a tank. The aero-ejector, which dimensions are given in Table 1, is placed on top of the tank, its outlet orifice directed to the tank bottom (Fig. 3). It is fixed on a rod that can slide through the upper part of the tank: this assembly enables

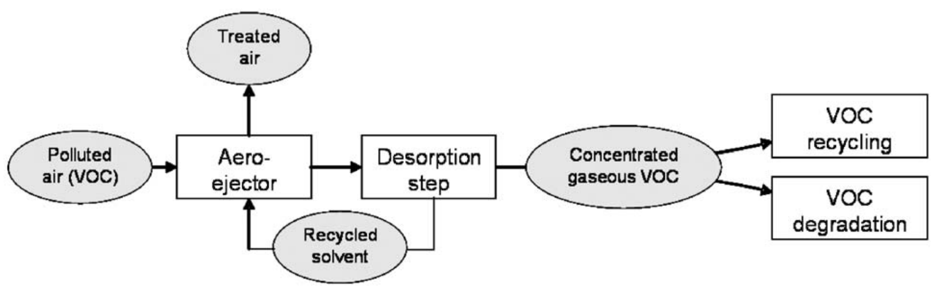

Fig. 2. Overview of the two processes developed in our laboratory to treat waste gas containing VOC.