www.icheme.org/cherd
doi: 10.1205/cherd05062

0263–8762/06/$30.00+0.00

Trans IChemE, Part A, December 2006
Chemical Engineering Research and Design, 84(A12): 1166–1179

HYDRODYNAMIC CHARACTERISTICS OF GAS–LIQUID EJECTORS

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In the present work, experimental investigations have been carried out on ejectors employing gas (air) as a motive fluid and liquid (water) as the entrained fluid. A semi-empirical model has been developed to predict the liquid entrainment rate taking into account, (1) the compressible nature of air, (2) pressure drop for two phase flow and (3) losses due to changes in cross sectional area. The effects of gas velocity, liquid level in the suction chamber, nozzle diameter, throat height and throat diameter on the liquid entrainment, entrainment ratio and pressure drop have been investigated. It has been observed that the liquid entrainment rate increases with an increase in the liquid level in the suction chamber. It was also found to increase with an increase in the gas velocity. The ratio of throat cross-sectional area to the nozzle cross-sectional area (area ratio) was found to be a critical parameter. The results have been explained on the basis of pressure profiles. The values of liquid entrainment rate predicted from the semi-empirical model were found to be in good agreement with the experimental measurements.

Keywords: hydrodynamics; multiphase flow; ejector; entrainment; pressure drop.

INTRODUCTION

Ejectors, jet-nozzles and similar devices are used for dispersion of gas in liquid. These are essentially co-current flow systems, where simultaneous aspiration and dispersion causes continuous formation of fresh interface and generation of large interfacial area of contact between phases. In gas–liquid ejectors, the motive fluid is pumped through a nozzle at a high velocity. As per the Bernoulli's principle, a low pressure region is created just outside the nozzle. The entrained fluid is, therefore, sucked into this region. The mixing of the motive fluid jet emerging from the nozzle and the entrained fluid leads to the dispersion in the throat. The diffuser section at the end of the mixing tube/throat helps in pressure recovery. The entire assembly (nozzle, converging section, mixing tube/throat and diffuser) is collectively called the ejector. The two phase dispersion issuing out of the ejector is either sent to a separator or a reactor vessel or a holding tank, which provides additional contact between phases. The motive fluid jet performs two functions, namely, it develops suction for entrainment of the secondary fluid and provides energy for the dispersion of one phase into the other. Ejectors produce high mass transfer rates by generating small bubbles/droplets, which can then be injected into a reaction vessel thereby further improving the contact between phases (Cramers and Beenackers, 2001). Compared to other gas–liquid contacting systems like stirred tanks and bubble columns, ejectors have a favourable feature like self sucking of one fluid and its efficient dispersion, resulting in large values of the volumetric mass transfer coefficient (Zahradnik *et al.*, 1997; Havelka *et al.*, 2000). In the chemical industries, ejectors are used to entrain and pump corrosive liquids, slurries, fumes and dust-laden gases, which otherwise are difficult to handle (Acharjee *et al.*, 1975). Jet ejectors can also be used for mass transfer operations like gas absorption or stripping, and so on (Ben Brahim *et al.*, 1984).

High values of mass transfer coefficients and interfacial area enable a substantial reduction in the size (and hence capital cost) of the contactor. The benefits of high values of mass transfer coefficients are particularly important if the intrinsic rates of chemical reactions occurring are very high and mass transfer controlled regime prevails. A majority of the published literature on ejectors deals broadly with the design and performance of steam and liquid-jet ejectors. The work reported on gas–liquid jet ejectors with gas as the motive fluid and liquid as the entrained fluid is scanty.

Many gas–liquid operations that employ sieve trays [Figure 1(a)] can possibly be retrofitted using several ejectors [Figure 1(b)] to generate higher mass transfer coefficients and thereby get higher throughput from existing columns (this can be achieved at the cost of higher pressure drop). For example, in the chemical exchange process

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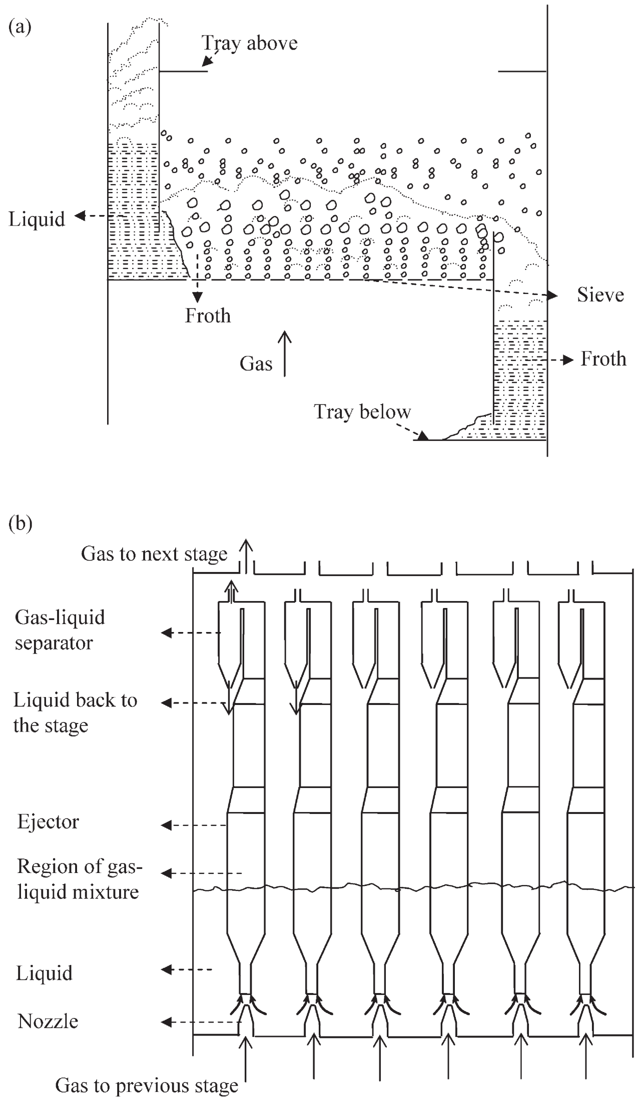

Figure 1. (a) Schematic diagram of gas–liquid dispersion in sieve tray. (b) Schematic diagram of retrofitted ejector tray in a sieve tray.

producing heavy water, a synthesis gas mixture of nitrogen and hydrogen is contacted with liquid ammonia at high pressure and low temperature. The deuterium absorption from the gas mixture into the liquid ammonia takes place in the presence of KNH_2 as a catalyst. Deuterium is present in gaseous hydrogen as HD at a concentration of about 100 ppm. HD dissolves into the liquid phase and reacts with ammonia to form deuteriated ammonia. The rate of this isotopic exchange reaction in the presence of KNH_2 is very fast as compared to the gas–liquid mass transfer rate (at the temperature and catalyst concentration employed on the industrial scale). The rate of mass transfer, therefore, becomes the controlling step in the overall process. If sieve tray columns [Figure 1(a)] are used, then it would require large number of trays (owing to low mass transfer coefficients $\sim 0.01\ s^{-1}$) and would increase the fixed cost of the process. To produce higher mass transfer coefficients, ejectors [Figure 1(b)] can be employed using high gas velocities. Due to the larger values of mass transfer coefficients ($\sim 1\ s^{-1}$) smaller number ejector trays suffice to achieve given degree of HD transfer. Such ejector trays are utilized in the heavy water production (Dave *et al.*, 1997). The important design parameters for such contactors would be the entrainment rate, pressure drop, hold-up of the phases, and so on. With this motivation, studies were undertaken to investigate hydrodynamics of gas–liquid ejectors with gas as the motive fluid.

PREVIOUS WORK

Most of the previous work carried out on gas–liquid jet ejectors employs liquid as the motive fluid and gas as the entrained fluid. Based on the flow direction, there are three types of ejectors reported namely vertical up-flow, vertical down-flow and horizontal flow. Several authors have performed detailed experiments and have predicted the entrainment rate empirically. The correlations developed by various researchers for their respective geometries using the dimensional analysis are given in Table 1. The form of most of these correlations is similar but with a wide variation in the exponents of different terms. For example, the exponent of area ratio varies from 0.07 (Bhutada and Pangarkar, 1987) to 0.68 (Acharjee *et al.*, 1975). In other words, these correlations are highly specific to the nozzle-throat geometry under investigation. Bhutada and Pangarkar (1987) reported four different correlations, one each for four throats investigated by them.

Bhat *et al.* (1972), Acharjee *et al.* (1975), Cunningham (1974), Biswas *et al.* (1975), Ben Brahim *et al.* (1984), and Mandal *et al.* (2005) have attempted to predict the entrainment rate based on momentum and energy balances across different sections of the ejector. Table 2 shows the geometry used and the correlations obtained through such analysis. However, these are at best semi-empirical, as they contain fitted constants. The empiricism in their work comes from (1) fitted loss coefficient, K', (2) the pressure recovery factor, β and (3) the correlation between K' and β. From the analysis of the previous work, it can be said that the relationships for mass ratio predictions are semi-empirical and depend on the geometry, fluid property, operating conditions.

Mandal *et al.* (2005) assumed that the entrained gas as ideal and isothermal. The energy loss coefficient across the nozzle was obtained from the energy balance. The pressure energy, kinetic energy and energy dissipation per unit mass of the liquid and gas were considered in the energy balance. No mixing was assumed in throat and diffuser and hence all the energy losses were only the frictional losses. The values of K_{ejt} back calculated from the data of ejector efficiency given by Mandal *et al.* (2005) were in the range 0.06–0.1 for the various geometries investigated by the authors. This indicates that the contribution of the work for gas compression and the hydrostatic head are very small. The pressure profiles in our ejector are shown later also confirm these observations that the pressure drop in the throat and the straight tube section are much smaller as compared to the pressure losses in the converging and the diverging sections.

The range of total pressure drop across the ejector measured experimentally in this work has been 0.04 to 0.8 atm. The pressure drop across the ejector is significant when compared to the inlet pressures that range from