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Hydrodynamic aspects of ejectors

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Abstract

The use of ejectors as a gas–liquid contacting device has been reported to give higher mass transfer rates than conventional contactors. Computational fluid dynamics (CFD) modeling studies were undertaken to understand the hydrodynamic characteristics with reference to the ejector geometry. The CFD model also provides a basis for quantifying the effects of operating conditions on the ejector performance. CFD studies show that at low value of area ratio (ratio of throat area to nozzle area), due to the larger diameter of the water jet, the annular area available for air flow reduces, causing recirculation of the entrained air within the converging section of the ejector. On the other hand, for higher values of area ratio, due to smaller diameter of the water jet, the momentum transfer to the air decreases and all the entrained air cannot be forced through the throat. As a result, the net air flow rate going into the throat for both area ratios is small. Thus there is an optimum area ratio for the maximum air entrainment rate. The air entrainment rate correlates with pressure difference between the air entry and throat exit for a wide variety of ejector geometries and operating conditions. The overall head loss factor and the ejector efficiency can be predicted a priori.

Keywords: Fluid mechanics; Multiphase flow; Hydrodynamics; Momentum transfer; Ejector; Entrainment

1. Introduction

In chemical process industry, efficient gas–liquid contacting is essential in processes such as hydrogenation, chlorination, etc. Due to their favourable mass transfer and mixing characteristics, ejectors are being increasingly used in the chemical and biochemical industries. Fig. 1 shows a typical ejector system consisting of nozzle, suction chamber, converging section, throat and pressure recovery section for gas–liquid contact where one phase (primary or motive fluid, typically liquid) is pumped into the system at high velocity through a nozzle from the top or bottom of the vessel. As per the Bernoulli's principle, a low-pressure region is created in the suction chamber. The secondary or entrained fluid, typically a gas phase, gets sucked into this chamber. The gas and liquid phases get mixed and a gas–liquid dispersion is created in the mixing tube. A diffuser at the exit of the ejector throat helps in pressure recovery. When the secondary fluid gets sucked into the suction chamber, the gas and liquid flows are initially coaxial consisting of an annular secondary fluid flow around a core of the primary fluid jet. This jet flow persists for a certain distance in the mixing tube. At a particular location, the jet flow changes into a froth flow. Beyond this location, the secondary fluid is dispersed in a continuous primary fluid stream. The change from coaxial jet flow to froth flow is called "mixing shock" (Witte, 1969). A part of the kinetic energy of the flow is dissipated in the shock creating the gas–liquid dispersion. The dispersion finally disengages into two separate fluid phases in the tank.

The high-energy dissipation rates, due to the mixing shock, result into much smaller bubble diameters and consequently into very high interfacial area ($\sim 2000\,m^2/m^3$) as compared to that in a conventional stirred tank (Malone, 1980). Ejectors thus, give better gas–liquid mass transfer rates and subsequently higher rates of reaction (Leuteritz et al., 1976). Ejectors have been used for gas sparging in

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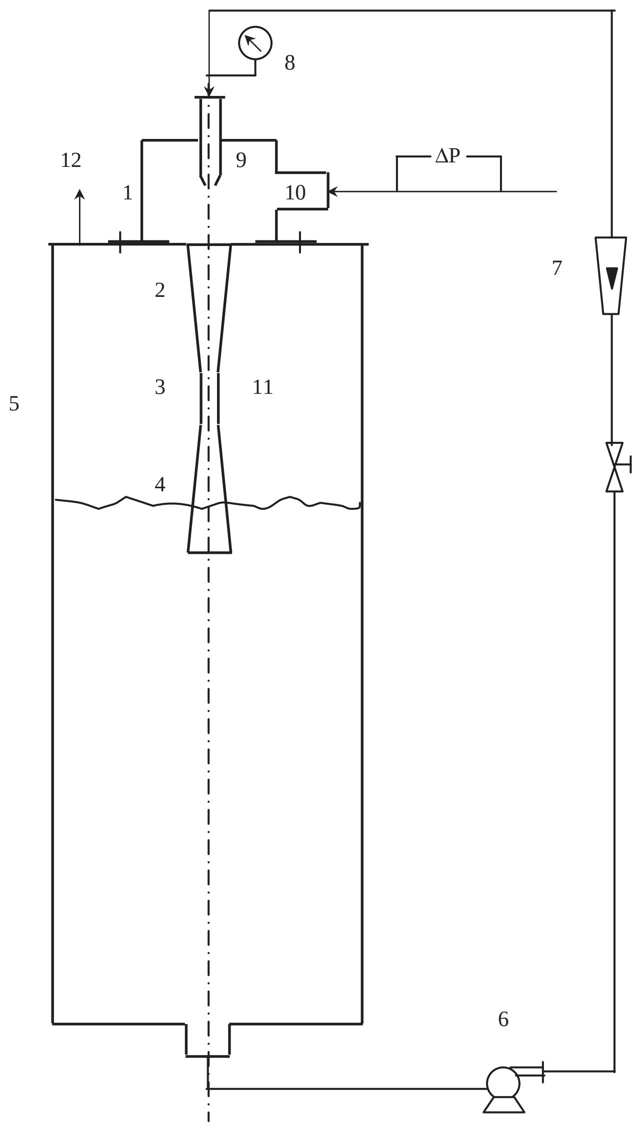

Fig. 1. Schematic representation of the ejector system being used as the dead end system: (1) suction chamber; (2) entry or converging section; (3) throat; (4) pressure recovery cone or section; (5) vessel; (6) liquid circulation pump; (7) flow meter for liquid; (8) pressure gauge for liquid; (9) nozzle; (10) suction pipe for gas; (11) diffuser; (12) gas outlet.

bubble columns (Zahradnik et al., 1982a,b, 1985; Rylek and Zahradnik, 1984; Havelka et al., 1997) and in aerobic fermenters (Moresi et al., 1983).

Many researchers applied the momentum balance and mass balance equations across the ejector to characterise the rate of gas entrainment (Davies et al., 1967; Bhat et al., 1972; Acharjee et al., 1975; Biswas et al., 1975; Ben Brahim et al., 1984; Mukherjee et al., 1988). The air entrainment rate is usually correlated by dimensional analysis using dimensionless groups such as $\Delta P/\rho_e U_e^2$ (ratio of the energy supplied by the motive fluid, i.e., the pressure drop, to the momentum gained by the entrained fluid), $(D_T/D_N)^2$ (ratio of the throat area to the nozzle area), and $g\mu_m^4/\rho_m\sigma_m^3$ (related to the physical properties of the motive fluid).

The effects of different operating conditions such as nozzle velocity, pressure drop, and ejector geometry parameters on the performance of ejectors have been experimentally investigated by several researchers (Jackson, 1964; Davies et al., 1967; Bhat et al., 1972; Biswas and Mitra, 1981; Rylek and Zahradnik, 1984; Bhutada and Pangarkar, 1987; Bhutada, 1989; Bando et al., 1990; Havelka et al., 1997).

Table 1 summarizes various empirical correlations for estimation of air entrainment rate, i.e., M_r (mass ratio of entrained gas to motive liquid). Most of these correlations have a similar form, where only the exponents of various terms differ with the difference in the nozzle and the diffuser geometries and the range of variables. For example, the exponent of $(D_T/D_N)^2$ ratio varies from insignificant 0.07 (Bhutada and Pangarkar, 1987) to 0.68 (Acharjee et al., 1975). Similarly, the exponent for the ratio of the energy supplied by the motive fluid to the energy gained by the entrained fluid varies from -0.135 to -0.82. These correlations are specific to the nozzle–diffuser geometry and may not be applicable to other ejector geometries with the same confidence. This fact is amply clear, as Bhutada and Pangarkar (1987) have reported five different correlations, one for each of the five diffusers investigated by them. It may be pointed out, that although the principle of an ejector has been well understood, practically all authors adopted an empirical approach to evaluate the exponents by fitting the experimental data. Although the role of pressure drop is well recognized, there was no systematic way of relating it to the entrainment rate.

There is thus a need to develop a better understanding of hydrodynamics of the ejector systems. Computational fluid dynamics (CFD) modeling approach is therefore utilized in this study to understand the fluid dynamics, and the effect of operating parameters from the first principles. In particular, the ejector geometry (nozzle diameter, type of diffuser entry, throat length, etc.) and the operating conditions, such as nozzle velocity, pressure drop, etc., are investigated for their effect on air entrainment rate.

The ejectors reported by Bhutada and Pangarkar (1987) are considered for the simulation. These authors have reported the effect of many parameters over a wide range on the performance of the ejectors and the data have been useful for CFD validation and for comparison with simulated values.

2. CFD modeling strategy

There are two approaches for the numerical calculation of multiphase flows: the Euler–Lagrange approach and the Euler–Euler approach. In the latter approach, different phases are treated as interpenetrating continua and this approach has been adopted for the model. The conservation equations have similar form for all phases in this approach. There are two Euler–Euler multiphase models: the Mixture model and the Eulerian model.