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STUDY OF JET APPARATUS OPERATION WITH PHASE INVERSION

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Abstract. *The paper considers three operational modes of a nozzle-ejector jet system. The study suggests modeling gas-liquid injection as gas permeation through a suspension of liquid droplets in forward flow. In this case, the process will be analogous to gas flow through a fluidized bed. The research determines a pressure drop through the well-known Ergun equation, which is applicable over a wide range of Reynolds numbers. The authors identify the depth of gas-liquid layer formation during phase inversion based on theoretical studies. For the jet apparatus most frequently used in gas-liquid ejector reactors. The authors calculated the ejector length at which phase inversion occurs.*

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Introduction

Jet apparatuses are finding increasing application in many industries. In chemical technology, such devices are used for heat and mass transfer processes, and as reactors for fast chemical reactions. One of the most reliable and accurate methods for evaluating the efficiency of gas-liquid apparatuses is the chemical method. It is based on determining the effective interfacial contact area, i.e., the phase interface actually involved in the mass transfer process [1-3]. This method is based on the chemisorption of oxygen from air. It allows determining the process rate and the ‘sulfite number’. Compact dimensions enable metal savings and high specific productivity without reducing the time required to complete the oxidation process [4].

Main body

The gas-liquid mixing device comprises a housing, an injection chamber, a liquid spray nozzle, a disperser, and a mixer made as a vertical pipe with varying cross-sections. The apparatus can operate over a wide range of working medium parameters, allowing regulation of the process hydrodynamics. An important parameter characterizing the ejector's efficiency is the efficiency coefficient (η), defined as the ratio of energy transferred to the gas flow to the energy expended by the motive flow [5-7]. The operating principle is as follows: the liquid under pressure is fed into the nozzle, atomized, and entrains gas entering the injection

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chamber. The resulting gas-liquid mixture passes through the ejector-mixer. In the ejector, contact between liquid and gas occurs with a developed surface of atomized liquid [8]. Depending on the ejector's operating mode, its geometric parameters, and the pressure differential across the nozzle, the ejector can produce a gas-liquid two-phase flow with different liquid-to-gas ratios. The two-phase flow may have either a dispersed liquid phase or a dispersed gas phase [9-11].

Based on the ratio of the nozzle throat area to the ejector throat area, such jet apparatuses are proposed to be classified as follows [2] (Fig. 1):

1. If $S_n/S_{ej} < 0.0013$, the liquid phase is always continuous in such jet apparatuses (Fig. 1a).
2. If $0.0013 < S_n/S_{ej} < 0.741$, such jet apparatuses may have either continuous gas or liquid phase (Fig. 1b), i.e., phase inversion occurs.
3. If $S_n/S_{ej} > 0.741$, the liquid phase is always dispersed in such jet apparatuses (Fig. 1c).

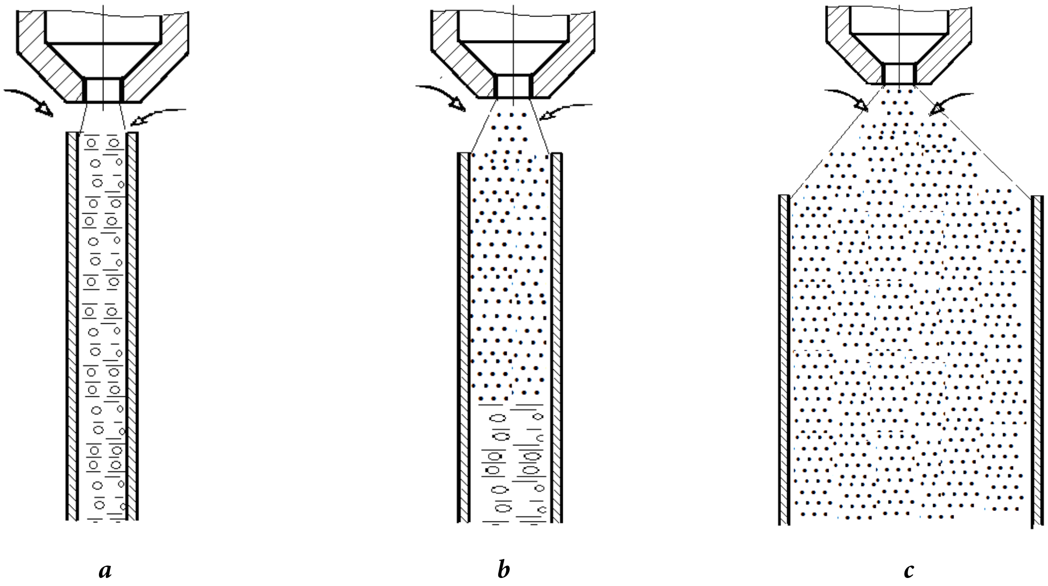

Fig. 1. Classification of jet apparatuses based on the ratio of nozzle throat area to ejector throat area

Of particular interest is the jet apparatus demonstrating phase inversion (Fig. 1b). It enhances mass transfer efficiency in gas-liquid systems without modifying the apparatus dimensions. This improvement results from increased mass transfer coefficients through elimination of backmixing and creation of effective contact zones between phases [12-14].

Some researchers suggest that complete (100%) mass transfer between phases occurs during both emulsion formation (during bubbling) and emulsion breakdown [15].

This work investigates the hydrodynamics of a jet apparatus comprising a nozzle and flow channel (ejector), specifically examining the interaction mechanism between the motive (liquid) and entrained (gas) streams within the ejector.

The study suggests modeling gas-liquid injection as gas permeation through a suspension of liquid droplets in forward flow. In this case, the process will be analogous to gas flow through a fluidized bed. The pressure drop can be determined using the well-known Ergun equation, which is applicable over a wide range of Reynolds numbers.

In the ejector's initial section (Fig. 2), we isolate a dz-height element.

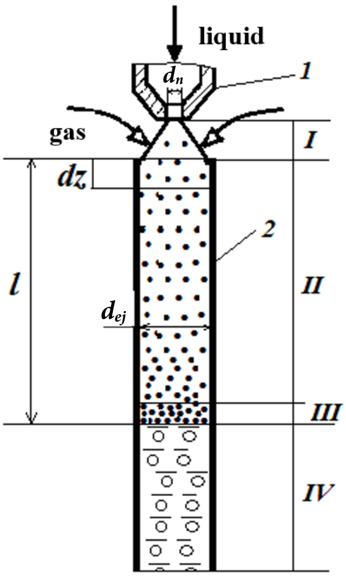

Fig. 2. Scheme of the jet apparatus with nozzle and ejector: 1 – nozzle; 2 – ejector.

The apparatus has four distinct zones:

- free jet zone;
- constrained moving zone of two-phase flow with dispersed liquid phase;
- gas-liquid emulsion formation zone;
- two-phase flow zone with dispersed gas phase.

The force driving liquid particles equals the vector sum of forces acting on particles within the specified volume.

$$F = G + F_{\text{ap}} - F_{\text{c}}, \qquad dF = dG + dF_{\text{ap}} - dF_{\text{c}}, \tag{1}$$

where dG – is particle gravity force;

dF_{ap} – is Archimedes force;

dF_{c} – is drag force.

$$dG = dm_l \cdot g = \rho_l \cdot dV \cdot g,$$

where ρ_l – is liquid phase density, kg/m^3;

$$dF_{\text{ap}} = dm_g \cdot g = \rho_g \cdot dV \cdot g,$$

where ρ_g – is gas phase density, kg/m^3;

$$dG - dF_{\text{ap}} = \left(\rho_l - \rho_g\right) \cdot dV \cdot g = \frac{\left(\rho_l - \rho_g\right) dm_l}{\rho_l g}.$$

Equation of motion:

$$\frac{dm_l dV}{d\tau} = \frac{\left(\rho_l - \rho_g\right) dm_l}{\rho_l g} - dF_c,$$

$$dF_c = \left[150\frac{(1-\varepsilon)^2}{\varepsilon^3}\cdot\frac{\mu_g\left(v_l - v_g\right)}{d_d^2} + 1{,}75\frac{(1-\varepsilon)}{\varepsilon^3}\frac{\rho_g\left(v_l - v_g\right)^2}{d_x}\right] S_{ej} \cdot d_z, \tag{2}$$

where ε is medium porosity;

μ_g is gas viscosity, Pa·s;

S_{ej} is ejector cross-sectional area, m^2.

We simplify the equation by neglecting the terms: $\frac{(\rho_l-\rho_g)dm_l}{\rho_l g}$ and $150\frac{(1-\varepsilon)^2}{\varepsilon^3}\cdot\frac{\mu_g(v_l-v_g)}{d_d^2}$ due to their small magnitude, and assuming $v_g = 0$, we obtain:

$$\rho_l V_l \cdot dV_l = -1{,}75\frac{(1-\varepsilon)}{\varepsilon^3}\frac{\rho_g}{d_x}S_{ej}\cdot v_l^2\cdot d_z. \tag{3}$$

Since $\varepsilon = 1 - \frac{V_l}{S_{ej}\cdot v_l}$, variable substitution can be performed in equation (3):

$$v_l = \frac{S_n}{S_{ej}}\cdot\frac{v_{l0}}{1-\varepsilon},$$

$$v_l = \frac{S_n}{S_{ej}}\cdot v_{l0}\frac{d\varepsilon}{1-\varepsilon}.$$

The variables in equation (3) can then be easily separated, allowing us to write:

$$d_z = -\frac{\rho_l}{\rho_g}\cdot\frac{d_d}{1{,}75}\cdot\frac{\varepsilon^3}{1-\varepsilon}d\varepsilon.$$

For the liquid to decelerate sufficiently from ε_0 to ε_{cr}, the ejector length must exceed a certain value determined by the equation:

$$l \geq \frac{\rho_l}{\rho_g}\cdot\frac{d_d}{1{,}75}\int_{\varepsilon_{cr}}^{\varepsilon_0}\frac{\varepsilon^3}{1-\varepsilon}d\varepsilon.$$

Integral $\int_{\varepsilon_{кр}}^{\varepsilon_0}\frac{\varepsilon^3}{1-\varepsilon} = \int_{\varepsilon_{кр}}^{\varepsilon_0}\frac{\varepsilon^3}{-\varepsilon+1} = \left(-\frac{\varepsilon^3}{3}-\frac{\varepsilon^2}{2}-\varepsilon\right) - \ln(\varepsilon-1) - \frac{\varepsilon_0^3}{3} - \frac{\varepsilon_0^2}{2} - \varepsilon_0 - \ln(\varepsilon_0 - 1) + \frac{\varepsilon_{cr}^3}{3} - \frac{\varepsilon_{cr}^2}{2} - \varepsilon_{cr} - \ln(\varepsilon_{cr}-1) = \frac{\varepsilon_{cr}^3-\varepsilon_0^3}{3} + \frac{\varepsilon_{cr}^2-\varepsilon_0^2}{3} + (\varepsilon_{cr}-\varepsilon_0) + \ln\frac{\varepsilon_{cr}-1}{\varepsilon_0-1}$.

Thus,

$$l \geq \frac{\rho_l}{\rho_g}\cdot\frac{d_d}{1{,}75}\left[\frac{\varepsilon_{cr}^3-\varepsilon_0^3}{3} + \frac{\varepsilon_{cr}^2-\varepsilon_0^2}{3} + (\varepsilon_{cr}-\varepsilon_0) + \ln\frac{\varepsilon_{cr}-1}{\varepsilon_0-1}\right].$$

We will perform calculations for the jet apparatus most commonly used in gas-liquid ejector reactors with nozzle and ejector diameters of $d_n = 12$ mm and $d_{ej} = 25$ mm, respectively.

The initial porosity will then be:

$$\varepsilon_0 = \left(1 - \frac{S_n}{S_{ej}}\right) = \left(1 - \frac{12^2}{25^2}\right) = 0{,}77.$$

The critical porosity is determined based on droplet packing in the gas-liquid emulsion formation zone [10]:

1. for dense packing: $\varepsilon = 0.259$;
2. for loose packing: $\varepsilon = 0.476$;
3. for granular materials, the average porosity is taken as $\varepsilon = 0.4$.

The droplet diameter d_d is determined depending on the Reynolds number $Re = \frac{v_l\cdot d_n\cdot\rho_l}{\mu_l}$, where v_l is the liquid velocity at the nozzle exit, calculated by:

$$v_l = \varphi_n\sqrt{\frac{2\cdot p_n}{\rho_l}},$$

where φ_n is the velocity coefficient (φ_n = 0.95...0.97), p_n is the nozzle pressure (Pa); ρ_l is the liquid density (kg/m^3).

For 2280 < Re < 18280, the droplet diameter can be determined from $\frac{d_d}{d_n} = \frac{18,3}{Re^{0,59}}$, = Re > 20000, increasing flow velocity and decreasing liquid viscosity practically don't improve spray quality, and the ratio $\left(\frac{d_d}{d_n}\right)$ can be taken as ~0.06 [4].

At nozzle pressures are above 0.1 MPa and velocities v_l > 13 m/s, Re > 150000, so we use $\left(\frac{d_d}{d_n}\right) = 0,06$. Thus, the droplet diameter becomes $d_d = 0,00072$ m.

Considering the critical porosity value of droplets, the integral value will be:

1)
$$\int_{\varepsilon_{cr}}^{\varepsilon_0} \frac{\varepsilon^3}{1-\varepsilon} = \frac{0,259^3 - 0,77^3}{3} + \frac{0,259^2 - 0,77^2}{2} + (0,259 - 0,77) + \ln\left(\frac{0,259 - 1}{0,77 - 1}\right) = 0,250.$$

2)
$$\int_{\varepsilon_{cr}}^{\varepsilon_0} \frac{\varepsilon^3}{1-\varepsilon} = \frac{0,476^3 - 0,77^3}{3} + \frac{0,476^2 - 0,77^2}{2} + (0,476 - 0,77) + \ln\left(\frac{0,476 - 1}{0,77 - 1}\right) = 0,234.$$

3)
$$\int_{\varepsilon_{cr}}^{\varepsilon_0} \frac{\varepsilon^3}{1-\varepsilon} = \frac{0,400^3 - 0,77^3}{3} + \frac{0,400^2 - 0,77^2}{2} + (0,400 - 0,77) + \ln\left(\frac{0,400 - 1}{0,77 - 1}\right) = 0,242.$$

The length of the ejector will accordingly be:

1)
$$l_1 \geq 0,32 \cdot 0,250 = 0,080 \text{ m}.$$

2)
$$l_2 \geq 0,32 \cdot 0,234 = 0,075 \text{ m}.$$

3)
$$l_3 \geq 0,32 \cdot 0,242 = 0,0774 \text{ m}.$$

According to the calculation results, regardless of the values of critical droplet porosity, the depth of the ejector at which phase inversion occurs is practically the same in all calculations.

Conclusions

The obtained results can be applied to heat and mass transfer calculations both in jet apparatuses and in gas-liquid reactors where such types of jet apparatuses are used.

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