OPTIMAL DESIGNING OF MASS TRANSFER APPARATUSES
WITH JET-FILM CONTACT DEVICES

A. V. Dmitriev,[1] O. S. Dmitrieva,[1] and I. N. Madyshev[2]

A design of a jet-film contact device developed for increasing the uniformity of liquid and gas phase distribution and enhancing mass transfer efficiency is described. The influence of the width of the drain cup on the mass transfer efficiency and hydraulic resistance is analyzed.

Keywords: *contact device, mass transfer, efficiency, hydraulic resistance.*

The demand for chemical, petrochemical, and oil-gas refinery products has been growing steadily, but the efficiency of the currently operating columnar mass-transfer equipment is inadequate because this type of equipment was designed a decade back for a relatively small load. Increase of load causes intensive entrainment of the liquid and "flooding" of the column. Enhancement of the efficiency of the apparatuses by increasing their diameter leads to increase in transverse nonuniformity of gas and liquid flows through the apparatus and decrease in mass transfer efficiency [1].

A possible way of solving the problem without loss of efficiency is to use apparatuses with forward flow scheme of interaction of flows, for example, columnar apparatuses having forward flow vortex contact devices [2–4]. These apparatuses are characterized by vigorous interaction of the phases, a wide range of steady operation, and relatively low liquid entrainment, but their notable demerit is high specific power energy consumption resulting from high hydraulic resistance.

New types of contact devices for minimizing liquid entrainment by gas stream and increasing phase contact surface with minimal hydraulic resistance are required for enhancing the efficiency of columnar mass transfer apparatuses. The design proposed in [5] meets these requirements.

The jet-film contact device, shown in Fig. 1, consists of parallel square drain cups *1*, the supports for which are vertical baffles *2* with slots. The drain cups are placed horizontally in a checkered fashion, forming a tray, and, as a result of misalignment of the cups that form a plate underneath, a checkered configuration of the cups is formed along the vertical line. Retrose lobes *3* in the form of round segments are made in the cup bottoms for distribution of the liquid over the surface of the vertical baffles *2*.

The proposed contact device operates as follows. The liquid flows through a multiplicity of retrose lobes in the form of jets and drains onto the vertical baffles lying below.

A steady liquid level is maintained in the cups. The liquid spreads over the surface of the vertical baffles with the formation of a stable film flow, whereupon it comes into contact with the rising gas stream coming from the plate bottom. The formed film breaks up upon collision with the surface of the liquid inside the cups. This produces a developed constantly regenerated phase contact surface, which depends on the presence of relatively small gas bubbles in the liquid layer and on the drops flying out from the surface.

The distance between the drain cups lying at the same level is equal to the width of the drain cup, and this maintains a uniform flowage for gas passage, which reduces hydraulic resistance of the proposed jet-film contact device.

[1] Kazan State Power Engineering University, Kazan, Russia; e-mail: ieremiada@gmail.com.
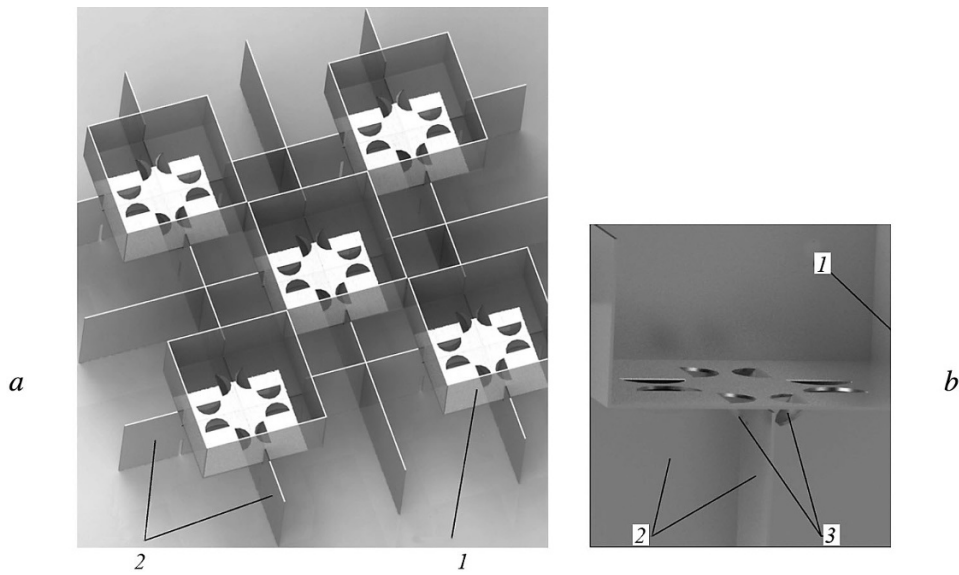[2] Kazan National Research Technological University, Kazan, Russia.

Fig. 1. Jet-film contact device: *a*) view from above; *b*) enlarged view of drain cup bottom.
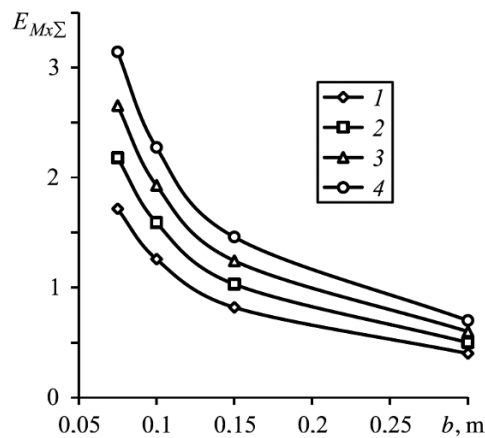

Fig. 2. Jet-film contact device efficiency as a function of drain cup width at the efficiency of one contact stage E_{Mx1}: *1*) 0.4; *2*) 0.5; *3*) 0.6; *4*) 0.7.

For ease of fabrication, the drain cups have a square shape in the transverse section. Thus, heat and mass transfer processes in both liquid and gas phases can be accelerated in an apparatus of simple design by organizing interaction between the gas and the liquid.

An important stage of designing mass transfer apparatuses having jet-film contact devices is determination of optimal width of the drain cup for ensuring a high mass transfer efficiency with a relatively low hydraulic resistance and metal content of the proposed apparatus. The apparatus design allows for installation of several contact stages in the same interplate space on account of reduction of the drain cup width because significant entrainment of liquid drops does not occur even at average gas flow velocity of 7 m/sec.

The presence of additional contact stages at the same occupied height makes it possible to enhance the overall mass transfer efficiency substantially, but reduced drain cup width leads to virtually proportional increase in hydraulic resistance and metal content of the proposed apparatus. Because of this, the aim of the performed numerical studies was to determine the optimal width of the drain cup, taking account of the influence of the above-noted factors.
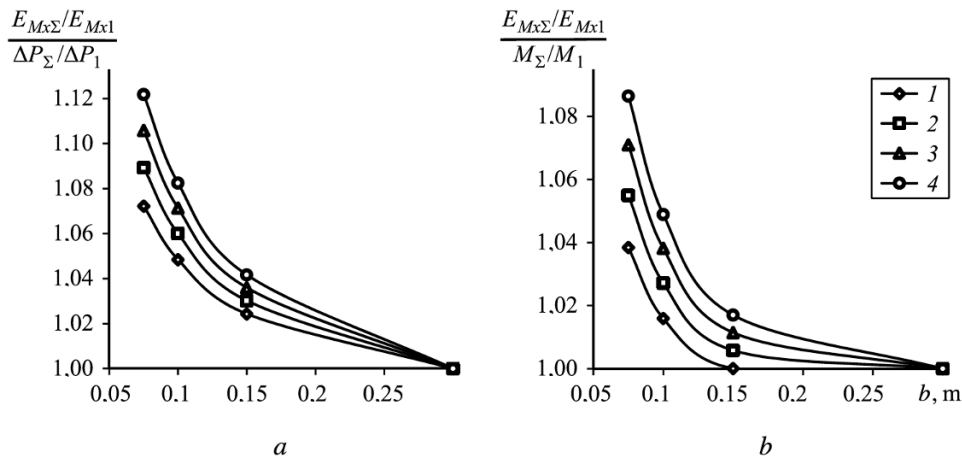
Fig. 3. Ratio of change in mass transfer efficiency to change in hydraulic resistance (*a*) and metal content of the equipment (*b*) as a function of drain cup width at the efficiency of one contact stage: *1*) 0.4; *2*) 0.5; *3*) 0.6; *4*) 0.7.
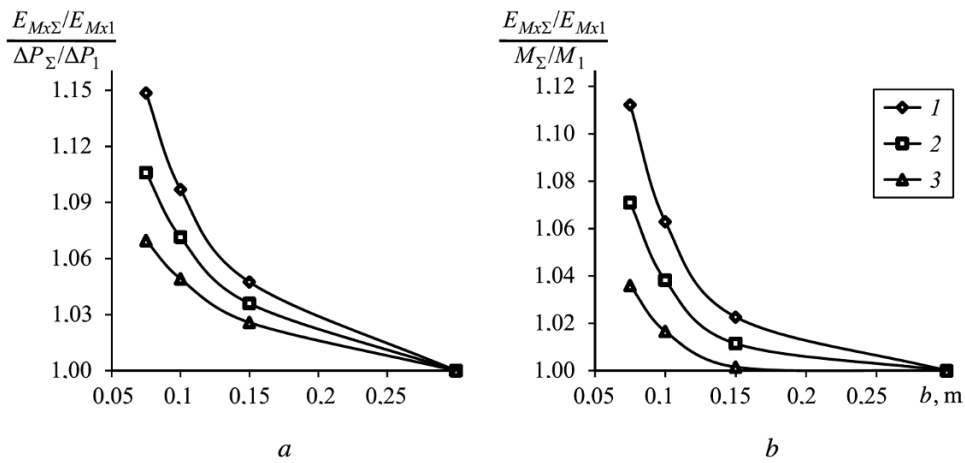

Fig. 4. Ratio of change in mass transfer efficiency to change in hydraulic resistance (*a*) and metal content of the equipment (*b*) as a function of drain cup width at the reflux ratio: *1*) 5.6; *2*) 7.0; *3*) 9.0.

The Murphree contact stage efficiency in liquid phase can be determined by the equation

$$E_{Mx1} = \frac{x_1 - x_2}{x_1 - x^*(y_1)}, \tag{1}$$

where x_1 is the initial concentration of the distributed component in the liquid phase (at the contact stage inlet); x_2 is the final concentration of the distributed component in the liquid phase (at the contact stage outlet); and $x^*(y_1)$ is the equilibrium concentration of the distributed component in the liquid phase.

From Eq. (1), we get the final concentration of the distributed component in the liquid phase:

$$x_2 = x_1 - E_{Mx1}[x_1 - x^*(y_1)]. \tag{2}$$

For the number *n* of contact stages, let us determine the final concentration of the distributed component in the liquid phase at the outlet of the *n*th stage by the equation

$$x_{n+1} = x_n - E_{Mx1}[x_n - x^*(y_n)]. \tag{3}$$

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Then, the total efficiency of the n stages compared to the efficiency of one contact stage:

$$E_{Mx\Sigma} = \frac{x_1 - x_{n+1}}{x_1 - x^*(y_1)}. \tag{4}$$

Previous studies showed that the efficiency of the contact stage does not depend on the width of the drain cup (the change does not exceed 0.5%). In this connection, the efficiency of each contact stage can be taken as equal (with an accuracy that suffices for calculations) within the studied number of stages.

The efficiency n of the stages of the jet-film contact device was calculated with reference to fractionation of *ethyl benzene–styrene* mixture. In the calculations, the replacement of the contact stage lying above the feed tray in the rectification part of the column of diameter 5.5 m was modeled. In this case, the initial ethyl benzene concentration in the liquid phase was 50 wt.%, temperature of the column top, 45°C, and absolute pressure at the top, 5 kPa.

In the calculations, the drain cup width b was varied from 75 to 300 mm, the reflux ratio R, from 5.6 to 9.0, and the efficiency of one contact stage E_{Mx1} from 0.4 to 0.7.

The investigation results showed that the total efficiency of the jet-film contact device depends a great deal on the drain cup width, the efficiency of one contact stage, and, to a minor extent, on the reflux ratio.

Figure 2 illustrates the change in jet-film contact device efficiency as a function of drain cup width at the reflux ratio of 7.0.

The efficiency of one contact stage decisively affects the total mass transfer efficiency. For example, with rise in the efficiency of one contact stage from 0.5 to 0.7 the total mass transfer efficiency rises by 40.0–44.2% (depending on the drain cup width). It follows from the plots in Fig. 3 that in the whole range of the studied drain cup widths the mass transfer efficiency increase rate exceeds the hydraulic resistance (Fig. 3*a*) and metal content (Fig. 3*b*) increase rates. In this case, the influence of the efficiency of one contact stage is significant: for example, heightening of efficiency from 0.4 to 0.7 enables one to heighten efficiency indexes that take account of pressure loss (up to 1.69 times) and of increase in metal content (up to 2.25 times) at $b = 0.075$ m.

The reflux ratio does not have much effect on the total mass transfer efficiency: if the reflux ratio falls by 60.7%, the total efficiency rises by only 7.38% at $b = 0.075$ m. The reflux ratio, however, affects the complex characteristics $(E_{Mx\Sigma}/E_{Mx1})/(\Delta_{p\Sigma}/\Delta_{p1})$ and $(E_{Mx\Sigma}/E_{Mx1})/(M_\Sigma/M_1)$ significantly.

Thus, for example, at the minimal reflux ratio, the increase in mass transfer efficiency outstrips the increase in hydraulic resistance by 14.85% (Fig. 4*a*) and the increase in metal content, by 11.23% (Fig. 4*b*) at 0.6 efficiency of one contact stage.

The performed calculations showed that at all studied drain cup width values the mass transfer efficiency increase rate exceeds the rate of hydraulic resistance and metal content increase. The mass transfer efficiency increases with a decrease in drain cup width. Consequently, for designing apparatuses with jet-film contact devices, the drain cup width should be minimal. In practice, however, this will unavoidably lead to an increase in hydraulic resistance and metal content of the equipment. Because of this, the optimum width of the drain cup is its minimum width, at which the allowable pressure drop in the column (individual for each real process) is ensured.

Thus, use of the proposed jet-film contact devices will ensure higher column efficiency without loss of mass transfer efficiency in currently operating and planned equipment of chemical and oil-gas chemical plants.

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