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PROCESSES AND DEVICES OF CHEMICAL MANUFACTURES

Hydrodynamics and Mass Exchange in Vortex Rectifying Column

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Abstract—Results of an investigation of the hydrodynamics and the mass exchange on the contact steps with tangential vortex generator at a rectification of the ethanol–water mixture are presented. Dependences for computation of the hydraulic resistance, an interphase surface, and the efficiency were obtained.

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Large amount of the vortex contact steps are attractive for designing due to their high productivity and efficiency. The most typical schemes of the contact vortex devices are showed on Fig. 1. The contact steps equipped by the tangential vortex generator (Fig. 1c), the simplest in the production, and of comparatively low hydraulic resistance and of high efficiency have been studied in this paper. Gas moving through tangential channels of the vortex generator obtains rotary motion, and disperses into the liquid forming the revolving gas-liquid layer where intensive division of vapor bubbles and their renovation occur. Since the data for an available computation and designing of the vortex trays of the rectifying column are deficent occurred we performed an additional research.

EXPERIMETAL

The ethanol-water rectification occurred in the column composed of 22 vortex contact steps with a distance between the trays of 100 mm (Fig. 2). The diameter of the vortex generator *d* was 88 mm, a channel number *n* , 36, a channel width, 1 mm, height *l,* 8 mm, a slope of the channels to a generating line, 23°.

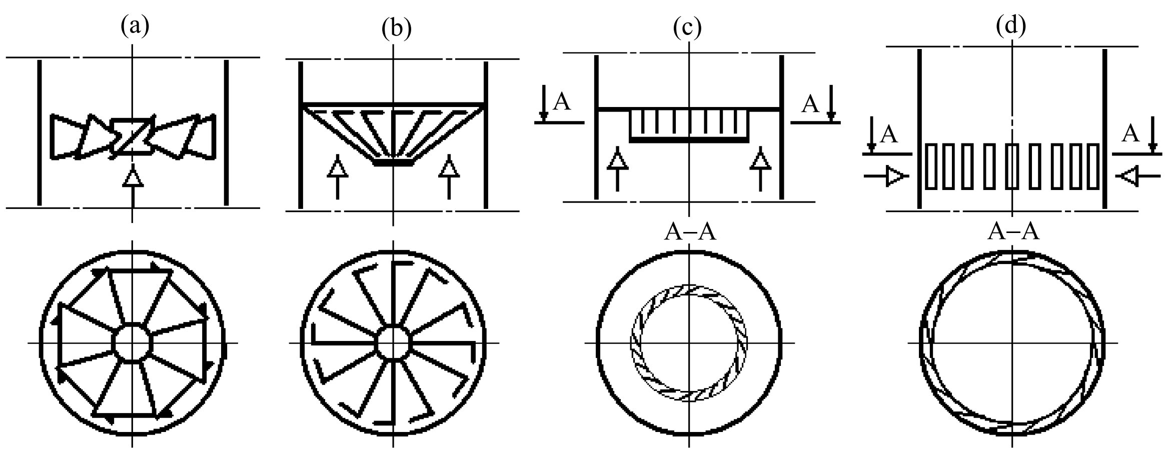

Fig. 1. Schemes of the vortex contact devices (a) axial vortex generator, (b) blade vortex generator; (c, d) tangential vortex generator.

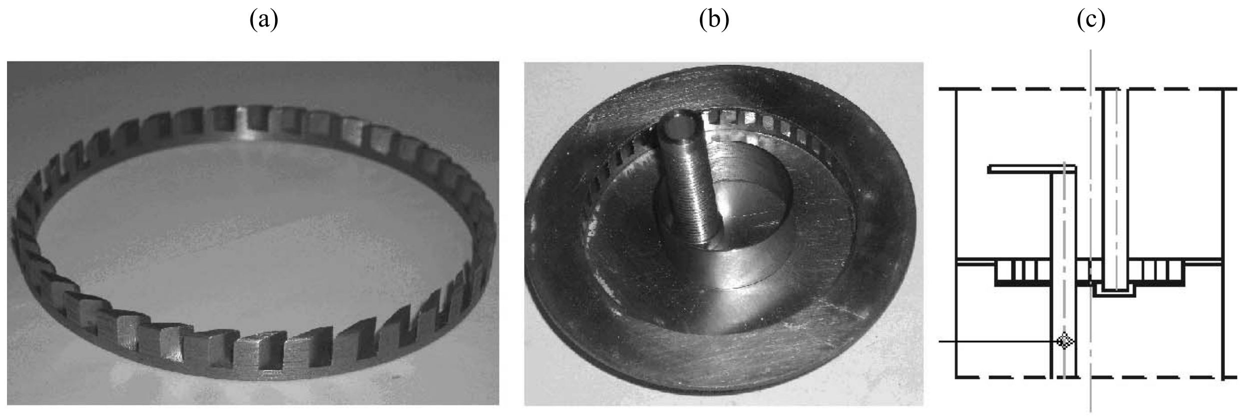

Fig. 2. The contact step with the tangential vortex generator (a) a picture of the vortex generator, (b) trays, (c) the scheme of the contact step.

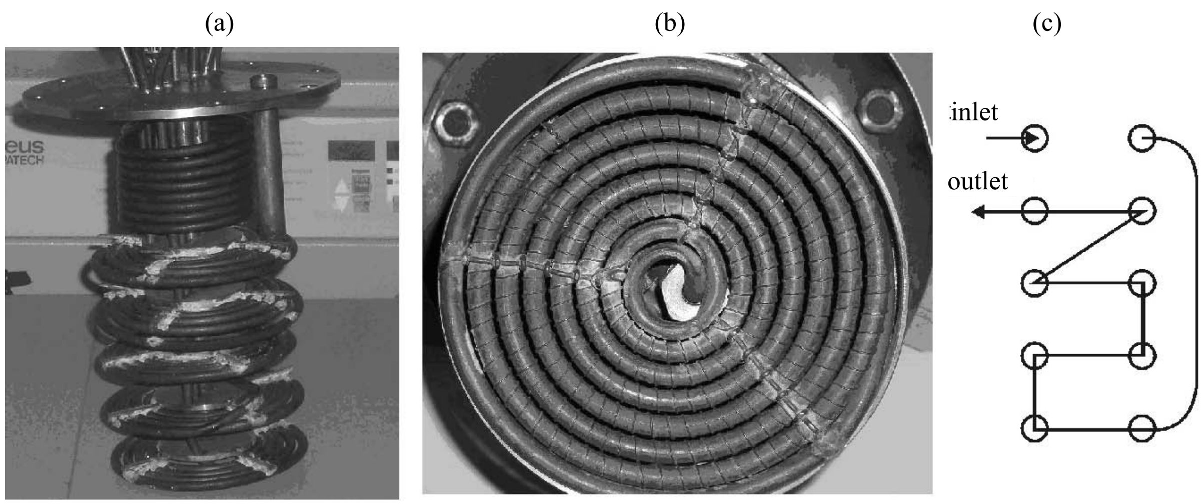

Fig. 3. The pictures of the built in reflux (a) a general view, (b) a view relative to the vapor inlet, (c) the scheme of the water connection.

The bottom section of the column of 0.2 m^3 volume as equipped with a jacket with electric heaters of 10kWt power built in. The flow of the fed water in a reflux drum with an initial temperature of 10°C was 0.04–0.10 $m^3 h^{-1}$. The hydrodynamics of the contact steps was studied also in an air-water system. Gas flow changed in a range of 2–50 $m^3 h^{-1}$ and was measured by a normal diaphragm. In this paper the built in reflux was made of copper pipes as spirals of Archimedes (Fig. 3). Such reflux assembling provides a required surface of the heat exchange at sufficiently small measurements, it increases a contact area of the vapor and the liquid, and avoids temperature tensions. The reflux surface of the heat exchange F was 0.35 m^2, a copper tube diameter 81 mm, a distance between the spirals 50 mm, a gap between the spiral tubes 1.5 mm. For removing the condensate film on the surface of the tubes a wire of 0.1 mm thickness was placed thereon with 35 mm step. An internal diameter of the reflux body was 120 mm. A scheme of a cooling water connection to the reflux is showed on Fig. 3c. It provided the temperature difference between the mixture vapors on the upper tray and the water removing the reflux in a range of 2–8°C in the dependence on a heat load.

A pressure drop on the step was controlled with a differential manometer.

An average surface diameter of gas bubbles we computed by a treatment of the pictures of the gas-liquid mixture in the step with the help of the following equation

$$d_S = \sqrt{\frac{\sum n_i d_i^2}{\sum n_i}}, \tag{1}$$

where n_i, d_i were an amount and the diameter of the gas bubbles.

The gas fraction in the liquid volume was determined according to

$$\varphi = (V_{gl}\ V_l)/V_{gl}, \quad (2)$$

where V_{gl} is the volume of gas–liquid mixture on the step; V_l, the liquid volume.

The interphase surface we computed according to the widely known dependence

$$a = 6\varphi/d_s.$$

The input heat was computed by equation

$$Q = Q_1 + Q_2, \quad (3)$$

where Q_1, Q_2 were the heat taken by water in the reflux, and in the condensator, respectively. Vapor flow over the column section was calculated by equation:

$$G_v = Q/r, \quad (4)$$

where r is the heat of mixture vaporization.

General number of transfer units and efficiency according to Murphree was determined by well known techniques. Efficiency of the step was computed by the measured concentration of ethanol on the upper step taking into account a real and theoretical number of the trays [1]. A coefficient of the mass transfer we calculated with the help of equation (5)

$$K_y = N_{0y}\ (G_v/a\ V), \quad (5)$$

where N_{0y} is the number of transfer units, G_v, the vapor flow, kg s^{-1}; a, the interphase surface, m^{-1}; V, the liquid mass on the step, kg.

The calculation of the coefficient of the mass transfer β_x was performed with the help of relation [2]:

$$1/K_y = 1/\beta_y + m/\beta_x. \quad (6)$$

We determined the concentration of ethanol with a refractometer and also with glass alcoholmeter.

RESULTS OF RESEARCH

As was established earlier [3] three main hydrodynamic regimes are observed: bubble, ring, and film depending on the gas flow. The ring regime of the stream originates on the step at the achievement value u_k of the gas velocity in the channels of the vortex generator. The liquid moves forward by the inertia to periphery forming rotating gas–liquid layer. In the course of the increase in the gas velocity, and as result of a rise of a centrifugal effect the decrease in the layer thickness and growth of its height occurs. The film regime with separate streams of the gas and the liquid is settled at reaching the value u_p of the gas velocity.

The ring regime of the stream is the most interesting since in this case the increase in the interphase surface is achieved at low values of the gas velocity and the resistance in the channels.

A relation for calculation of the gas velocity in the channels when the transfer into the ring regime occurs looks as

$$u_k = C\ (f/F)^{-0.8}\ (H/D)^{0.7}[\rho\ (1-\varphi)/\ \rho_g)\ \alpha^{0.19}, \quad (7)$$

where u_k is the gas velocity, m/s; F, the area of the contact step section, m^2; f, the area of the channel section in the vortex generator, m^2; H, a level of the gas–liquid mixture on the step, m, D, the step diameter, m, ρ and ρ_g are the gas and liquid densities, kg m^{-3}, α is the slope to a generating line, deg, $C = 0.0038$.

Equation (7) is applicable at the vortex generator diameter $R > 60$ mm, at a value of $\mu_l/\mu_g = 55–78$ and it enables computing the vapor velocity with accuracy of ±15%.

As experimentally found the transition from the ring regime to the film one is reached at a ratio of $u_k / u_p = 0.5$. The general resistance of the contact step was determined as:

$$P = P_d + P_w. \quad (8)$$

The resistance of the dry step

$$\Delta P_d = \xi \frac{\rho_g u^2}{2},$$

of the sprinkled step

$$\Delta P_w = \rho_g H(1-\varphi) + \Delta P_\lambda,$$

where ξ is a coefficient of the dry step resistance, u, the average gas velocity at the channel outlet, m/s; ρ_g, the gas density, kg/m^3; ΔP_λ, the pressure drops caused by the tangential tensions in the interphase surface, Pa; H, the

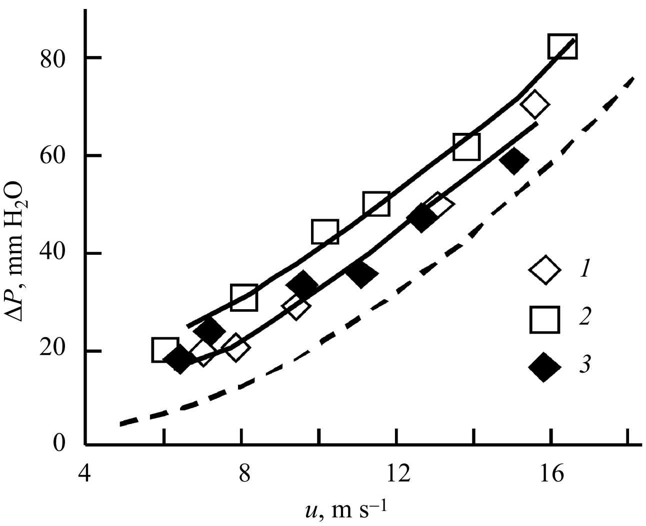

Fig. 4. Dependence of the sprinkled step on the gas velocity at D = 100 mm, n = 36, δ = 1 mm, l = 8 mm, α = 23°. The point *1–3*: (*1*) V = 100 ml; (*2*) 200; (*3*) 150 according to the data of distillation. A dashed line: resistance of the dry step.

height if the gas-liquid layer, m; φ, the gas content.

The coefficient of the dry tray resistance is

$$\xi = \xi_{in} + \xi_{out} + \xi_g + \xi_{turb}, \quad (9)$$

where $\xi_{in} = 0.5(1 - f/F)^{3/4}$ and $\xi_{out} = (1 - f/F)$ are the coefficients of resistance conditioned by gas compression and expansion that constitute an insignificant part of the summary value of ξ.

The coefficient of the resistance ξ_g depends on input and output conditions of the gas in the channels of the vortex generator and equals ξ_g = 0.6–1.

Value of ξ_{turb} caused by the flow turbulence, makes the largest contribution to the total hydraulic resistance of the step. Its value (Reynolds number > 1500) may be calculated by equation (10)

$$\xi_{turb} = 31\alpha^{0.75}\delta^{1.3}n^{1.3}R^{-2.5}, \quad (10)$$

where α is the slope, deg; δ, the gap value at the gas outlet from a slot, mm; n the number of the slots, R is the radius of the vortex generator, mm.

A decrease in the value δ leads to diminishing the scale of the turbulence and respectively of the resistance. An increase in the channel number n results in the growth of the resistance caused by their reciprocal influence on the vortex scale. The construction parameters and R determine a value of a rotational moment for the gas–liquid flow. At the growth of the radius in the vortex generator and upon a decrease in the slope of the channel the centrifugal effect on the gas–liquid layer rises that leads to division of the vortex and respectively to diminishing the coefficient of the resistance.

The investigation of the resistance of the rectifying column and the contact steps (Fig. 4) demonstrates that the contribution of the dry tray to the total P is 60–65%, and the influence of the head of water, 25–40%.

It is necessarily to increase a factor f/F and the radius of the vortex generator R, is order to diminish the slope of the channels, and the value of the gap and the slot number in order to decrease the hydraulic resistance of the step.

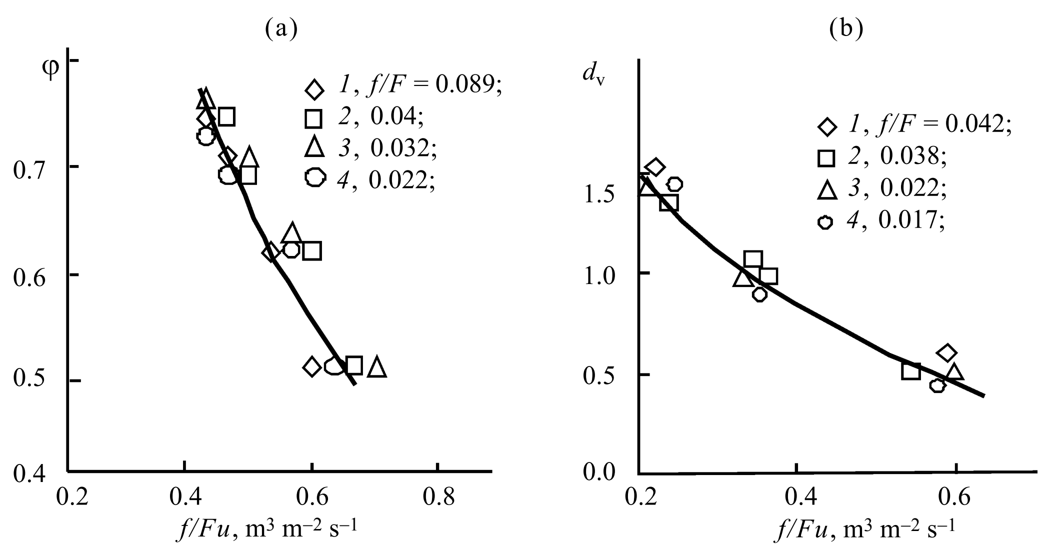

Fig. 5. Dependences of the gas content (a) and the bubble diameter (b) on the specific gas flow at D = 100 mm , V = 200 ml, δ = 1–2 mm; n = 4–36.

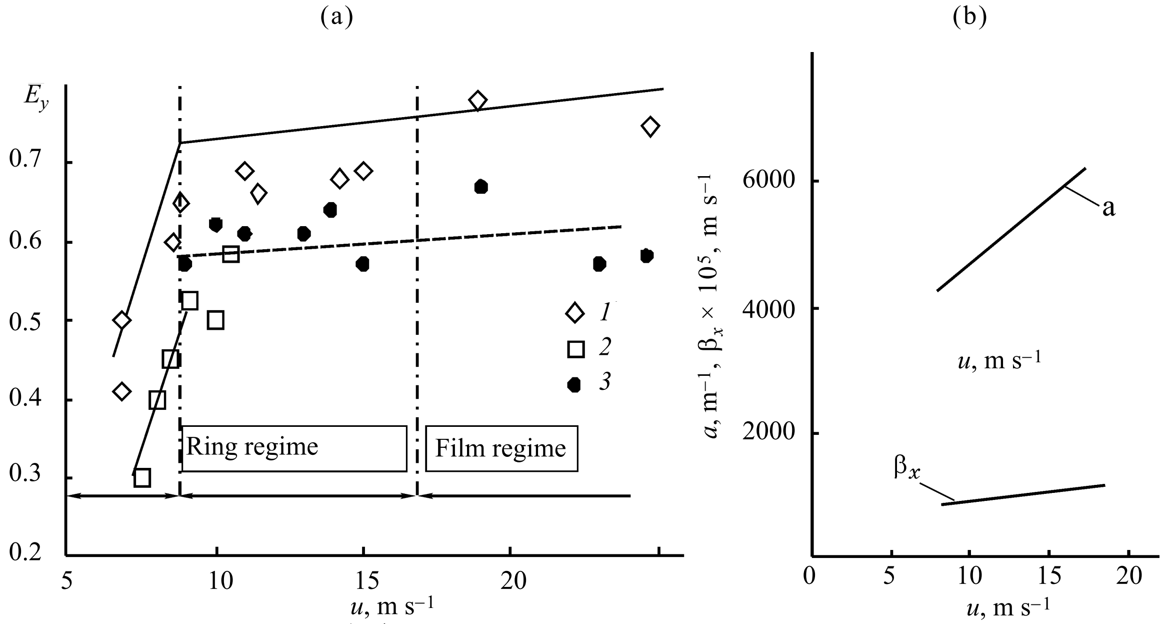

Fig. 6. The dependence of the efficiency of the contact step, interphase surface, and coefficient of the mass transfer on the gas velocity in the channel of the vortex generator at the reflux factor 0.8–2.5; d = 88 mm; n = 36; δ = 1 mm; V = 150 ml. (a) Experimental point *1–3*: (*1*) m = 0.75; (*2*) m = 0.1; (*3*) m = 0.2; (b) at f/F = 0.04.

The gas content and the bubble diameter of the gas in the liquid on the tray at the ring regime significantly depend on the factor f/Fu that characterizes a specific gas flow (Fig. 5). Hence we may suggest that the main division of the bubbles is performed by tangential tensions conditioned by the rotary movement of the gas–liquid flow in the tray. The value of the interphase surface was computed due to the data depicted on the Fig. 5 (Fig. 6b).

An efficiency of the rectification at the bubble regime on the 5th step of the distillation column was 0.3–0.4 and that does not contradict well-known data [2]. At the ring regime the efficiency of the contact step rose 1.7–2 times in comparison with bubble regime that is caused by an increase on the interphase surface and by the flow turbulence. An effect of the vapor velocity in the channel of the vortex generator on the efficiency is depicted on the Fig. 6a.

The efficiency computed by the number of the theoretical and real trays (point *3* on Fig. 6) whereas the tray efficiency (point *1* and *2*, Fig. 6a) changes in a sufficiently wide range. This confirmed well-known consideration about unequal efficiency of the contact trays along the height and about dependence, in many respects, of their properties on the physical properties of the studied mixture.

The coefficient of the mass transfer in the liquid phase ($\beta_x = (0.8–1)\times10^{-2}$ m s^{-1}) computed according to equations (5) and (6) are pictured in Fig. 6b. The tray efficiency as well as the coefficient of the mass transfer depend on the change in the gas velocity less than the interphase surface.

Treatment of the experimental data pictured on Fig. 7 enables developing the relation for computation of the number of the transfer unit looking as

$$1/N_{oy} = 0.6\,\mathrm{Pr}_v^{0.5} + 0.04\,\frac{mG}{L}\mathrm{Pr}_l^{0.4} \qquad (11)$$

where N_y is the number of the transfer units, Pr_v, Pr_l are the Prandtl numbers in the vapor and liquid phases. Similar equation was obtained earlier [4].

The efficiency of the contact tray diminishes upon a decrease of the reflux factor and the slope of an equilibrium curve (Fig. 7a). Relating $\lambda = mG/L > 1$ for an estimation of the contact tray efficiency we can assume equation [5] (curve *3* on Fig. 7a)

$$E_y = \frac{N_{oy}}{1 + N_{oy}}. \qquad (12)$$

In the area of the low values of parameter λ the

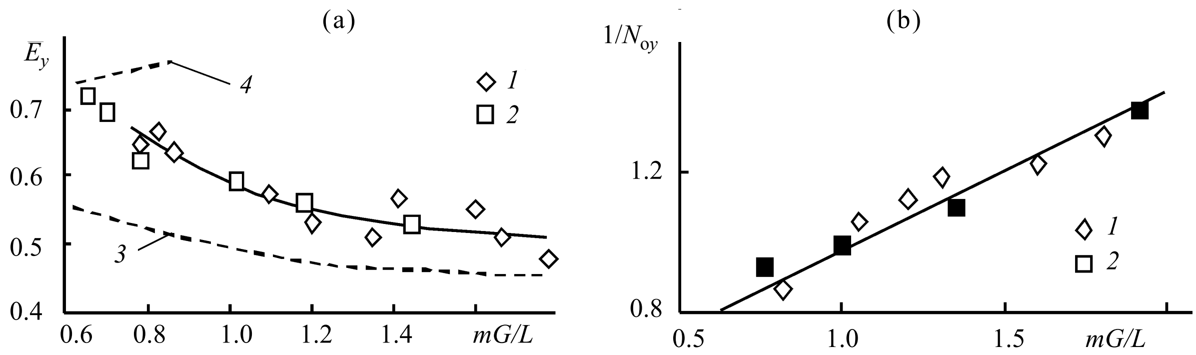

Fig. 7. The dependence of the efficiency of the contact trays and number of the transfer units on the parameter *mG/L* at $m = 0.7$; $n = 36$; $d = 1$ mm; $V = 150$ ml. The experimetal points *1–2*: (*1*) data of this work; (*2*) data of [4]. Curve *3* and *4*: (*3*) computation by equation (12), (*4*) by equation (13).

experimental values of the efficiency are fit to calculated ones according to equation (13) [6]

$$E_y = 1 - \frac{1 + \lambda}{\lambda + \exp\left[N_{oy}(1 + \lambda)\right]}. \qquad (13)$$

The presented data make it possible to design the vortex tray, to estimate the number of the contact steps, and to compute their hydraulic resistance.

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