Mass Transfer Coefficients in a Gas Phase in Volume of a Regular Nozzle with Drop Structure of a Gas-Liquid Stratum

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Abstract: In the paper, patterns of change of regime (gas stream, irrigation densities) and constructive parameters (step deployment of elements of a nozzle in the vertical and radial directions) are obtained for devices with regular nozzles of spherical, lamellar shapes and in the form of a tubular bundle. Optimal values of constructive nozzle parameters are determined, at which the regimes of simultaneous vortex of nozzle items in the course of the gas flow and vortex formation of independent nozzle elements in the radial direction. I want to mention especially the vortices formed in the flow of spherical and nozzle prismatic elements. The influence of the formation and interaction of the vortices on the size of the liquid droplets, which are the main structural element of the dispersed liquid phase in the apparatus of the design. Equations for calculating mass transfer coefficients in a gas phase and liquid diameters of formed drops are offered, based on the known laws of mechanics of gas and liquid.

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Keywords: mass transfer; regular nozzle; gas; liquid; vortices; diameter of drops.

1. Introduction

At the industrial enterprises for carrying out mass transfer processes (absorption, distillation, extraction) and contact cooling of gas and liquid got widespread packed columns along with disk-shaped devices. Regular and irregular packing are used in it as the contact devices. Irregular packing (Raschig rings, Pall, Berl saddles, packing of HY-PAK, CASCADE-RINGS and «Inzhekhim») (Senol 1995, Farahov 2009) have an increased flow friction. They have a comparatively small efficiency and are not able to operate with dirty gases and liquids.

Regular packing INTALOX, Sulzer, Koch, «Inzhekhim», Norton, «Vakupak» «Glitch -Grid», Mellapak, MellapakPlus, Mellagrid and netted packing BX and CY contain regular channels, owing to which they have some minimal flow friction and a high efficiency. However, they are subject to overgrowing by hard deposits.

The work (Serikuly 2013) shows the study results of hydrodynamic characteristics of apparatuses with a regular movable nozzle of cylindrical, lamellar and ball shapes, for obtaining the dependences for calculating the coefficients of hydraulic resistance, the number of retained fluid.

The aim of the research work is to study the hydrodynamic and kinetic characteristics of movable devices with a regular lamellar, cylindrical and ball shapes with dispersed details containing the liquid phase and to obtain the calculated dependences for the determination of mass transfer coefficients in the gas phase and the diameters of the drops.

In this regard, the task of the work includes an experimental research of mass transfer coefficients in the gas phase and droplet diameters in the movable devices with a regular nozzle of lamellar, cylindrical and ball shapes and obtaining the calculated dependences of examined parameters.

2. Material and Methods

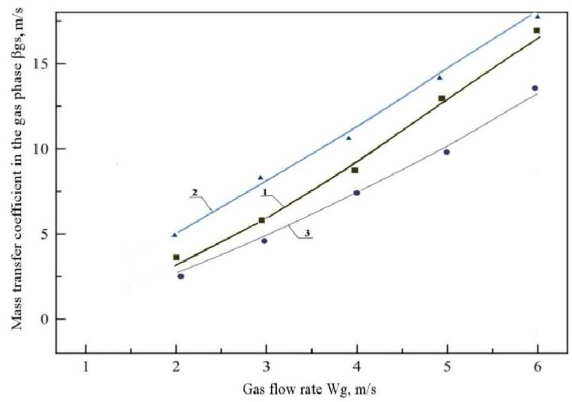
Studying of mass exchange characteristics of devices with the regional wire nozzle was carried out on the experimental installation including a column in diameter of 1,0 m and a height of the working space of 1,0 m (Serikuly 2013). Movements of gas and liquid streams were carried out in a counterblow mode. Installation was equipped with a gas blower providing the gas flow rate in the working space of the device W_g = 1–5m/s, the pump allowing to create the irrigation density of L = 10-75 $m^3/m^2 \cdot h$, devices for measuring the gas velocity, liquid flow rate, hydraulic resistance, psychrometers to measure the moisture content in the gas flow, thermometers and measured capacities.

To determine mass transfer coefficients in a gas phase referred to the section of the device β_{gs} or to its volume β_{gv}, a widely applied technique has been used, which is based on studying a process of adiabatic evaporation of water in the air (Ramm 1976). Experimental values of diameters of drops were determined by statistical processing of photos.

Research of mass transfer coefficients in a gas phase and diameters of drops was carried out for lamellar, tubular and spherical nozzle elements.

3. Results

The flow rate is one of the main factors influencing frequency of its pulsations. Consider the effect of the gas flow rate on mass transfer coefficients in the gas phase (β_{gs}).



● - is a ball at L=25 m3/m2·h; t_v/d_b=4,7; t_r/d_b=2;
■ - is a cylinder at L=25 m3/m2·h; t_v/d_c=2; t_r/d_c=2;
∆- is a lamina at L=25 m3/m2·h; t_v/b=2; t_r/b=2;
Figure 1 Dependence of the mass transfer coefficient in the gas phase β_{gs} from the velocity of gas Wg of devices with a regular mobile nozzle

The graphs of dependence of β_{gs} and diameters of drops $d_d=f(W_g)$ from W_g are presented in figure1 and 2, respectively. Analysis of these curves shows that intensity of mass transfer grows with increase of the gas flow rate. It is obvious, since in the case of a mass transfer limited by resistance of the gas phase, significant flow turbulence takes place, which reduces the diffusion resistance.

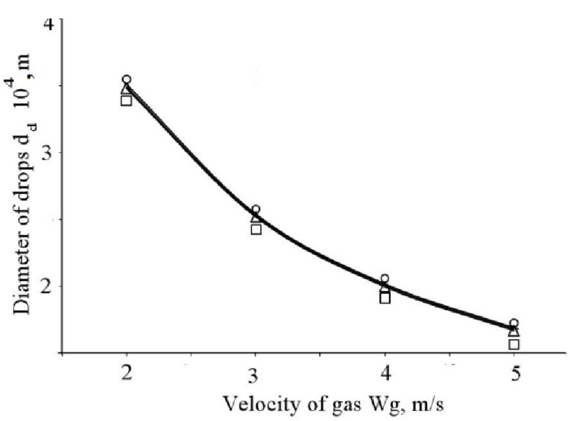


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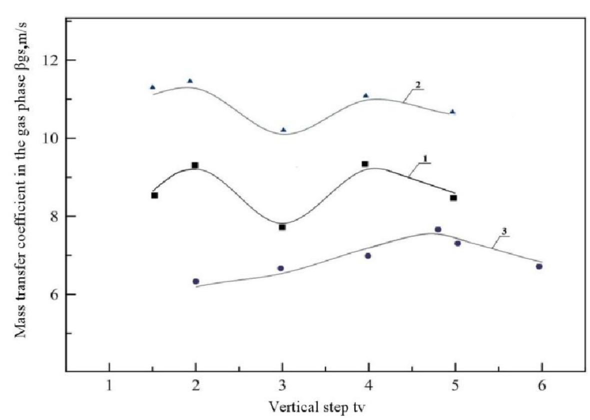
Figure 2. Dependence of diameter of drops of a liquid d_r 10^4 m from the gas velocity Wg

Moreover, structure of a gas-liquid layer undergoes a change, the average diameter of drops decreases (figure 2), and, hence, the interfacial turbulence increases. The increase of mass transfer coefficients β_{gs} (figure 1) occurs in all range of a studied field of rates of a gas flow. It is typical for the majority of mass exchange devices (Ramm 1976).

In the case of mass exchange limited by resistance of a gas phase, one chooses, if it is possible, higher velocities of gas, in the case when resistance is limited by a liquid phase, the gas flow rate plays less essential role. Work of devices with a regular mobile nozzle in a droplet mode is the most effective. Here, achievement of high values of mass transfer coefficients in the gas phase β_{gs} is possible under condition of acceptable carryover of spatter.

Values of mass transfer coefficients in the gas phase β_{gs} increase if density of an irrigation L increase. This is due to the fact that the surface of contact between phases is determined significantly by the surface of liquid drops, the number and diameter of which increases with increasing density L. In turn, growth of the drops quantity is caused by increasing the speed of liquid movement on a nozzle and intensity of inflow of fresh liquid in a contact zone. It is known ((Ramm 1976, Kafarov 1979), the increase in density of an irrigation at absorption of well soluble gases influences significantly on efficiency and causes additional expenses on pumping of liquid at increased values.



● - is a ball at L =25 m3/m2·h; t_r/d_b=2; Wg=4m/s;
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Figure 3. Dependence of a mass transfer coefficient in the gas phase β_{gs} from a vertical lead of t_v

Adhering to the general recommendations, the choice of optimal density of irrigation can be performed on the basis of experience data directly in the study of the absorption process of a gaseous component by the accepted absorber and data on hydrodynamics.

In addition to regime parameters (the velocity of gas Wg and the density of an irrigation L), relative position of nozzle elements (step deployment of elements of a nozzle in the vertical t_v /b and radial directions t_r /b) has a significant influence on the mass transfer process.

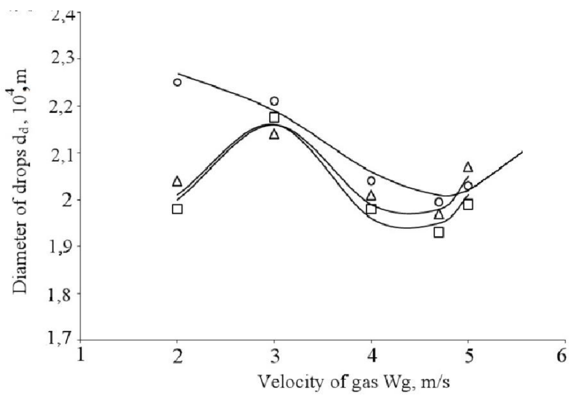

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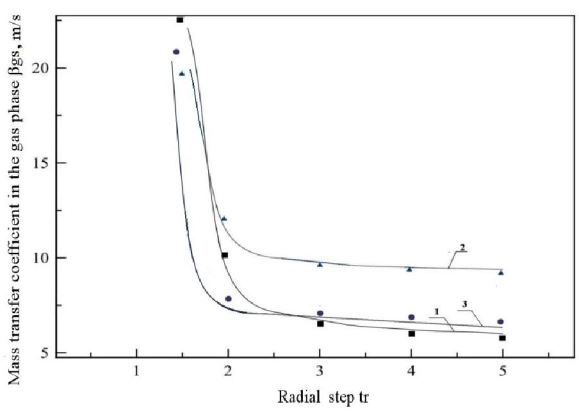
Figure 4. Dependence of the diameter of liquid drops d_d 10^4 m from the vertical step t_v



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Δ - is a lamina at L =25 m3/m2·h; t_v/b=2; Wg=4m/s.
Figure 5. Dependence of mass transfer coefficients in the gas phase β_{gs} from a radial step t_r

The increase in the radial step t_r /b from 2 to 4 leads to the fact that process of formation of vortices and vortex shedding depends on the width of streamlined elements and decrease of values of β_{gs} is proportional to the growth of a nozzle porosity.

In a series of studies of droplet diameters, it has been found that there are two plots of the curve changes at change of radial steps t_r (figure 6). To t_r <2 the diameters of drops are much lower than for $t_r \geq 2$. The obtained results are confirmation of the above-described mechanism of vortex formation, according to which the frequency of vortex shedding to the critical step t_r=2 is defined by the value of gap between nozzle elements in the radial direction, while exceeding the critical step leads to the fact that the vortex shedding frequency is determined by the size of streamlined elements of a nozzle. Therefore more powerful vortices with the high relative frequency of their failure at t_r >2 significantly contribute to the formation of small droplets than in the case where the vortices are formed behind the nozzle elements.

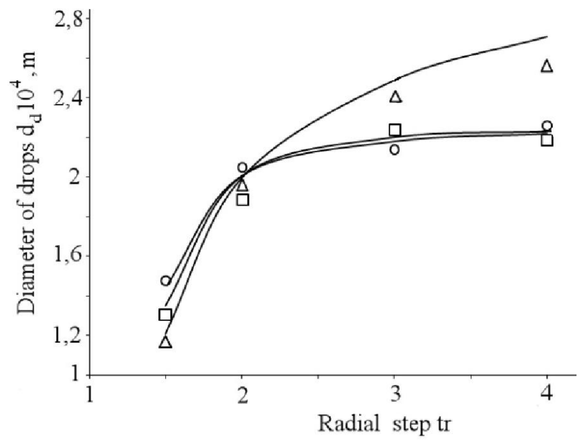

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Figure 6. Dependence of diameter of drops of liquid d_d 10^4 m on the radial step t_r.

The nozzle zone represents a system of streamlined bodies, so if the gas stream and the liquid interact in it, pulsating motion of the whole layer is generated. In addition, a separated flow of the gas stream is behind a drop and nozzle elements with a liquid film, resulting in deformation of the free surface of the interface. In this case, small vorticities occur in the boundary layer adjacent to the surface of contact between phases, which according to (Balabekov 2001) play a key role in the mass transfer. Intensity of mass and heat transfer, as in the dispersed flow and in a continuous one, depends on the depth of penetration of the vorticity, which is a measure of the thickness of the oscillating boundary layer.

Derivation of the equation for calculating the mass transfer coefficients in the gas phase is based on usage of the first Fick's law and the basic premises of the theory of locally isotropic turbulence by Kolmogorov-Obukhov (Kolmogorov 1941). As a result, we obtained the equation for calculating the mass transfer coefficients in the gas phase

The analysis of dependencies curves β_{gs} = f(t_v /b) (figure 3) indicates the presence of extreme values, moreover the curves of mass transfer coefficients in the gas phase for lamellar and tubular nozzles have two extrema achieved on t_v /b=2 and 4, whereas for a spherical nozzle, there is one extremum t_v /b=4,7. This is because the in-phase modes, characterized by a half-period and period, are achieved at indicated steps. The period mode inherent in the device with a regular spherical nozzle, and also half-period and period modes in devices with a lamellar and tubular nozzle are characterized by higher values of the mass transfer coefficients in gas and liquid phases. The maximum amount of vortices reproduced in these modes, the growth of their power promote intensive development of the interface surface because of the large number of crushable drops and films, that allows to intensify significantly the processes of mass transfer. Not-in-phase in the vortex formation leads to decrease of coefficients β_{gs}. Influence of steps of an arrangement of a nozzle elements on structural changes of disperse liquid phase illustrates visually the schedule of dependence of d_d =f (t_v) (figure 4).

As it is seen in figure 4, the minimum values of d_d are observed in the curves d_d=f (t_v) in the range of the vertical steps t_v from 2 to 6, corresponding to values of t_v =2 and 4 for the tube bundle and plates, as well as t_v/d_b=4,7 for the balls. It was noted above that approach of in-phase modes corresponds to these steps. These modes are characterized by the creation of powerful vortexes that crush jets into smaller drops. The in-phase mode is broken at other values of steps, the capacity of vortexes decreases and diameter of crushable drops grows.

Behavior of curves β_{gs} in the range of t_r /b from 1,5 to 4 (figure 3) is identical for all studied nozzles. A sharp decline of curves β_{gs} is in the range of t_r /b from 1,5 to 2, while for t_r /b>2 falling of curves occurs more smoothly. The increased values of mass transfer coefficients in the gas phase β_{gs} to a phase for t_r /b from 1,5 to 2 are caused by a considerable turbulization of a gas-liquid stream by the vortices, quantity of which increases in proportion to the width of a gap between streamlined elements. In this case the amount of withheld liquid also increases and hydraulic resistance grows.

$$\beta_{鎶}=\hat{A}_{\beta_{鎶}}\cdot\left[\frac{D_g^2\cdot C_k\cdot U_g^3\cdot\left(h_0-h_f\right)}{\varphi_c\left(t_b-h_f\right)\cdot d_d\cdot\nu_g}\right]^{1/4}, \qquad (1)$$

where D_g is the coefficient of molecular diffusion in m/s^2; C_k is the coefficient of resistance of a drop; U_g is the true velocity of the gas in m/s; h_0 is the amount of retained liquid (ARL) in the device, and h_f is a film component of ARL in m; φ_c is a gas content in the cell layer; d_d is the diameter of drops of liquid in m; $B_{\beta_{гs}}$ is the proportionality coefficient determined experimentally. The following proportionality coefficients were obtained by processing the experimental data: for a lamellar nozzle $\hat{A}_{\beta_{鎶}}=7,8\left(\frac{\varphi}{1-\varphi}\right)^{1/4}$; for a tubular bunch with round pipes $\hat{A}_{\beta_{鎶}}=8,68\left(\frac{\varphi}{1-\varphi}\right)^{1/4}$; for a ball nozzle $\hat{A}_{\beta_{鎶}}=7,97\left(\frac{\varphi}{1-\varphi}\right)^{1/4}$. Here φ is the gas content of a layer in the device. In the irrigated devices the error of calculated data by equation (1) with experimental (figures 4,5) were as follows: for the device with a tubular nozzle ± 14%; with sheet ± 15%; with ball ± 14%.

Mechanism of decomposition of liquid drops in the layer of a regular mobile nozzle is complex (Volnenko 2012) as crushing occurs there both because of deformation of drops, and under the impact of moving with a high speed drops on the nozzle and with each other. Depending on the kinetic energy of colliding particles and liquid particles of nozzle elements, both decay of drops, and sticking to the nozzle, and also the coalescence of the liquid particles can occur. Such constant and multiple change of acts of crushing and merging tends to equalization of the size of drops. Therefore estimating dependence of the average integral value of diameter of drops from basic parameters of the layer is of interest for the calculated equations.

The crushing mechanism of drops in an entire stream is explained (Volnenko 2012) based on the theory of locally isotropic turbulence. Applying the balance equation of the forces, operating on a drop, for calculating the diameter of drops of liquid, the following equation is obtained:

$$d_d=B_k\cdot\xi_L^{1/3}\frac{\rho_l^{1/6}\cdot\sigma^{1/3}\cdot d_{jl}^{2/3}\cdot U_g}{\rho_g^{1/2}\cdot U_{jl}^{5/3}}, \qquad (2)$$

here ξ_L is the resistance coefficient of an irrigated nozzle; ρ_g is the gas density, and ρ_l is the liquid density in kg/m^3; σ is the surface tension in N/m; d_{jl} is the diameter (m) and U_{jl} is the velocity (m/s) of a liquid stream; B_k is a correcting coefficient.

B_k =0,07 for a lamellar nozzle; B_k =0,067 for a tubular bunch with round pipes; B_k =0,072 for a ball nozzle.

4. Discussions

The study identified that as the velocity of the gas mass transfer coefficient in the gas phase are growing, and the diameters of drops falling. The mass transfer coefficients in a gas phase and diameters of drops grow with increasing the irrigation density. The increase in steps of an arrangement of the nozzle elements in the vertical direction leads to modes of simultaneous vortex formation (in-phase modes) which are achieved at t_v /b=2 and 4 for a lamellar and tubular nozzle, respectively and at t_v /b=4,7 for a spherical one. If steps of an arrangement of elements of a nozzle are changed in the radial direction, two domains are identified, differing with sources of vortex formation. For t_r /b<2, a source of vortex formation is the gap between nozzles, and for t_r /b≥2 it is the width of streamline nozzle bodies. Use of first Fick's law and the basic premises of the theory of locally isotropic turbulence by Kolmogorov-Obukhov allowed to obtain the equation for calculating the mass transfer coefficients in a gas phase, for which diameter of drops is determined based on the theory of locally isotropic turbulence and the balance equation of the forces operating on a drop.

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