OPERATING-DESIGN PARAMETERS ANALYSIS AND HYDRAULIC RESISTANCE CALCULATION OF VORTEX PACKED LAYER STRUCTURE APPARATUS

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ABSTRACT

Analysis of operation of apparatus with a movable packing and regular arrangement of packed elements in the volume of contact zone allowed create designs of apparatus with a combined regularly weighted packing, combining positive qualities of analogues.

The research results of hydraulic resistance of apparatus with a regular structure tubular packing and with a combined regularly weighted packing were compared. Depending on the gas flow velocity for apparatus with a regular structure tubular packing, the presence of three hydrodynamic modes (film-drop, drop, and drop entrainment) is noted. For apparatus with a combined regularly weighted packing, four hydrodynamic modes (stationary state of the packing, transient mode, mode of developed turbulence, and drop entrainment) were defined.

Analysis of the research results of design apparatus parameters with a regular packing elements arrangement in the contact zone volume allowed justify the steps of placing the packing elements in the vertical and radial directions. So, for the regular structure tubular packing apparatus, such steps aret_b/d=2 and 4, and for the radial step t_r/d=2.

Methods for calculating the hydraulic resistance, taking into account operating and design parameters, are proposed for the studied apparatus.

Key words: combined packing, hydraulic resistance, gas velocity, operating modes, design parameters, calculation method

INTRODUCTION

Currently, a large number of apparatus with a movable packing are known, among which are apparatus with a weighted, flowing, circulating packing, etc. Their development was aimed at creating their perfect designs that meet the basic requirements for heat and mass transfer apparatus. These include high intensity, stability of mass transfer characteristics under changing loads, constant efficiency during large-scale transition, simplicity of design and operation, versatility, insensitivity to pollution of the gases and liquids being processed, low energy intensity, material intensity, etc. [1].

However, apparatus with weighted and flowing packing have a number of disadvantages, the main of which are increased hydraulic resistance and significant longitudinal mixing. Apparatus with a circulating packing with a circular motion are difficult to manufacture and also have significant hydraulic resistance. Apparatus with a regular movable packing have no such disadvantages. The uniform distribution of packing on the strings in the contact zone volume can significantly reduce the hydraulic resistance [1].

One of the varieties of apparatus with a regular structure of the packed zone is an apparatus with a bundle of regular tubular packing [2]. Implementation of the contact apparatus in the form of a bundle of tubes, arranged across the gas-liquid flow motion, provides additional advantages, since in this case it is possible to supply heat directly to the contact zone of phases or to withdraw from it, which is a mandatory requirement for efficient conduct of many heat and mass transfer processes and chemisorption [1].

Another variety that is included in this class of apparatusis an apparatus with a combined regularly weighted packing [3,4]. Introduction of weighted ball contact elements to the regular structure tubular packing zone allows carry out mechanical cleaning of the internal packed zone surfaces, which may be important when working with gas and liquid flows polluted with solid particles that have enhanced adhesion properties.

MATERIALS AND METHODS

The known methods of measuring the hydraulic resistance using a well-type manometer and micro manometer were used for the research. To visualize the gas-liquid layer, photographing the working apparatus area was carried out.

RESULTS AND DISCUSSION

The hydraulic resistance research results were analyzed depending on the operating-design parameters of apparatus with a regular structure tubular packing and with a combined regularly weighted packing.

It is known that the main parameters determining the operation of packed heat and mass transfer and dust collecting apparatus are gas and liquid flows and design features of the contact zone [5].

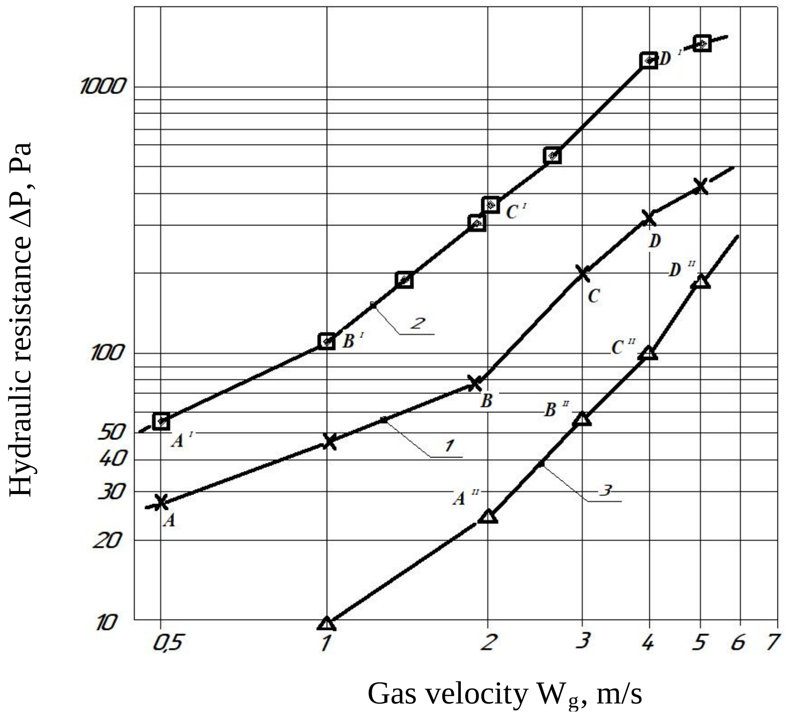
The research results of the hydrodynamics of apparatus with a bundle of regular tubular packing are available in the works [6-8]. There was also carried out research of the hydraulic resistance of apparatus with a combined regular-weighted packing (tubular-weighted (TW) and tubular-flowing (TF)), depending on the operating parameters.

Figure 1 shows a graph of the hydraulic resistance against the gas flow velocity in a logarithmic grid of coordinates for apparatus with a combined regularly weighted packing (TW and TF), as well as apparatus with a regular structure tubular packing [9].

As can be seen from the graph, as the gas flow velocity increases, the hydraulic resistance values increase. This is natural, since increase in the gas flow velocity affects the gas flow dynamic pressure growth and the gas-liquid layer high turbulization. Increase in the amount of liquid supplied leads to increase in the gas flow consumption to overcome the liquid friction.

In the specified ranges of change of operating parameters, the authors of the works [5-8] for apparatus with a regular structure tubular packing noted the presence of three hydrodynamic modes (film-drop, drop, and drop entrainment). We have defined four hydrodynamic modes (stationary state of the packing, transient mode, mode of developed turbulence, and drop entrainment) for apparatus with a tubular-weighted and tubular-flowing packing.

In the apparatus with a regular structure tubular packing at the gas flow velocity from 1 to 2.2 m/s, in a film-drop mode, the gas flow motion does not break the liquid flow nature that flows through the tubes in the form of a film.In the lower part of the tubes, the film disintegrates into large drops, which fall onto the lower layer and merge into a film. In the inter tubular space, the liquid is also in the form of large drops and jets.



Experimental conditions: TW and TF apparatus (one support-distribution grid; $t_b/d=4$; $t_r/d=2$; p_n= 600 kg/m^3; d_n = 0.015 m; H_{st}=0.03m; S_k/S_{ap}=0.28 m^2/m^2; L=15 m^3/m^{2}h); apparatus with a tubular packing ($t_b/d=2$; $t_r/d=2$; L=10 m^3/m^{2}h) [9]

1 - ΔP_{TW} – tubular-weighted packing; 2 - ΔP_{TF} – tubular flowing packing; 3 –ΔP_L– apparatus with a regular structure tubular packing [9].

Fig. 1. Dependence of the hydraulic resistance of apparatus with a combined regular-weighted packing and with a regular structure tubular packing on the gas velocity

In the apparatus with a tubular-weighted packing, the AB area (w_r from 0.5 to 1.8 m/s) and in the apparatus with a tubular-flowing packing, the$A^I B^I$area (w_r from 0.5 to 1 m/s) correspond to the stationary state of the packing layer. The existence of this mode for the TF apparatus in a narrower w_r range is due to the presence of a pyramidal (conical) plate in it, which contributes to the increased velocity of the introduced gas flow in the central part of the layer, where the packing begins to acquire mobility.This state corresponds to the beginning of the $w_{H,B}$. Layer weighting [10].

When the gas velocity isw_g= 2.2-4.0 m/s for the apparatus with a regular structure tubular packing, the drop mode is noted in which the dynamic pressure is sufficient to form waves on the film surfaces. The liquid films are first crushed into jets and then into drops. In the entire contact zone volume, there is a chaotic motion of drops, their collision between themselves, with the liquid film, and entrainment to the above rows of tubes.

At $w_r \geq w_{H,B}$the lifting force in the TW apparatus becomes sufficient for separating the packing elements from the grid. With increase in w_r, the number of weighted elements increases over the entire cross section, and the weighing in the TW apparatus has an uneven oscillatory character. This unstable mode is called transient. In Figure 1 it corresponds to the BC and B^IC^I areas.

As against the apparatus with a regular structure tubular packing, where the drop mode is maintained up to w_g = 4.0 m/s, in the apparatus with a combined regular-weighed packing within the CD, C^ID^I areas, an intense turbulent phase interaction is observed. Therefore, here begins the next mode called the developed turbulence mode, which is characterized by an intense motion of the packing, a significant layer expansion and a noticeable uniformity of phase distribution.

The critical gas velocity in all of the research counter-flow apparatus is limited by the amount of permissible drop entrainment (in the absence of a drop catcher) or by pressing a part of the packing to the upper grid to form a hanging dense layer, which leads to a sharp jump in the hydraulic apparatus resistance. This mode is called the drop entrainment mode (D, D^I, and D^{II} points).

The increase in the amount of liquid supplied in all ranges of change in the gas flow velocity leads to increase in energy consumption due to more work on its breakdown, and beginning of the modes is shifted towards lower gas velocities.

The beginning of flowing, or weighing in apparatus with a combined regular-weighted packing (B and B^Itransition points), substantially depend on the irrigation density L. The increase in the L leads to the change in $w_{n.f}$, or $w_{n.b}$, towards lower values w_r. In the transient mode, the ΔP growth depending on w_r somewhat slows down. This is explained by the oscillatory nature of the layer behavior, the liquid falls through the grid in large portions and, as a result, its delay decreases [10].

Research of hydraulic resistance, other hydrodynamic characteristics, and Euler number on the design parameters of a tube bundle [5-7, 9] have revealed the regularities described in the works [11, 12]. At flowing around solid bodies that are regularly arranged in the direction of flow, it is possible to achieve simultaneous vortex formation modes (in-phase modes) when the formation time and the vortex motion time behind the body chain coincide [11].This phenomenon is accompanied by increase in energy consumption. At the same time, the apparatus operation in the in-phase mode allows achieve significant efficiency of the processes (absorption, contact heat exchange and dust collection).

For the apparatus with a regular structure tubular packing, the extreme points corresponding to the achievement of simultaneous vortex formation modes are the tube positions in the vertical direction $t_b/d=2$ and 4 [5-8]. Therefore, in the work [9], studies of hydrodynamic characteristics, mass and heat transfer were carried out with a tube step in the vertical direction equal to $t_b/d=2$.

In order to carry out the research, in view of the weighted contact elements motion peculiarities in the tubular bundle intertubularspace, there was chosen the tube arrangement step in the vertical direction equal to$t_b/d=4$, which also ensures the in-phase mode achievement.

When studying the effect of radial steps between the tubes [6, 7, 9], another regularity was established [12]. The critical step value between solids, which determines the size and frequency of verticesformation is the gap width between adjacent bodies. Exceeding the critical step leads to the fact that each solid body forms vortices on its own and the width of a solid body determines their frequency. The critical step value in the radial direction for a tubular packing is $t_r/d=2$.

For the apparatus with a regular structure tubular packing, the loss of flow pressure spent on the vortices formation and interaction in the tubular bundle, on changing the gas flow direction, on the gas friction on the packing elements surface and the liquid film can be calculated as follows [13,14]:

$$\Delta P_L = \xi_L \cdot \frac{H}{t_b} \cdot \frac{\rho_g W_g^2}{2\varepsilon_0^2}, \quad (1)$$

Where H is the packing height, m; ρ_g – gas density, kg/m^3; ξ_L – resistance coefficient, taking into account the pressure loss in the interaction of vortices in the vertical and radial directions, on the gas friction on the packing elements surface and the liquid film; ε_0 – porosity of the packing row

$$\varepsilon_0 = 1 - \frac{d}{t_p} \quad (2)$$

ΔP_L experimental data processing[6,7,14] allowed obtain practically identical calculated dependences to define the coefficients ξ_L:

$$\xi_L = 0{,}25 \cdot \theta_b \cdot \theta_r \cdot \mathrm{Re}_l^{0{,}1}, \quad (3)$$

In the formula (3) Re_l – Reynolds number:

$$Re_l = \frac{U_l \cdot d_{ekv}}{\nu_l}, \quad (4)$$

where U_l=L/3600 – the liquid velocity, m/s; ν_l – kinematic liquid viscosity coefficient, m^2/s; L – irrigation density, m^3/m^2·h; d_{ekv} – equivalent packing diameter, m.

The equivalent packing diameter is defined as an equivalent diameter of channels through which the gas moves [6, 7, 14]:

$$d_{ekv} = \frac{4 \cdot t_b \cdot t_r - \pi d^2}{\pi d}, \quad (5)$$

The volume tubular packing porosity is defined by the formula:

$$\varepsilon = 1 - \frac{\pi d^2}{4 t_r \cdot t_b} \quad (6)$$

The coefficient characterizing the vortices interaction degree in the vertical direction θ_b for all types of packing elements regularly arranged in the gas motion direction [6, 7], is defined by the equation:

$$\theta_b = 0.85 + 0.15 \sin\left[\frac{\pi}{2}\left(\frac{4 t_b \cdot S\ell}{m_k} + 1\right)\right], \quad (7)$$

where *Sl*– Strouhal number for the tubular elements $Sl = 0,2$; m_k–parameter taking into account the vortex formation, form of streamlined elements and decrease in the vortices velocity. For the tubular elements

$$m_k = 0.44\left(1 - \exp\left(-t_b\right)\right) \tag{8}$$

The coefficient, characterizing the vortices interaction degree in the radial direction and taking into account the change in the vortex formation frequency, θ_r can be defined by the formula [6,7]:

$$\theta_r = \frac{t_r - \lambda}{t_r - d} \tag{9}$$

The pulse elements arranged in the same row perpendicular to the streamlined flow contribute to the vortices formation with scales λ. There are two cases for discretely arranged bodies in the same row perpendicular to the streamlined flow: att_r>2d λ=d; att_r<2d λ= t_r-d.

The hydraulic resistance of apparatus with a combined regular-weighted packing consists of the resistance of a tubular bundle and a weighted ball packing:

$$\Delta P_L = \Delta P_{tr} + \Delta P_{pN} \tag{10}$$

The flow pressure losses spent on the vortices formation and interaction in the tubular bundle of the apparatus ΔP_{tr} can be calculated by the equation (1).

By processing the experimental hydraulic resistance data, practically identical calculated dependence was obtained to determine the coefficients ξ_L:

$$\xi_L = 0,53 \cdot \theta_b \cdot \theta_r \cdot \mathrm{Re}_l^{0,1} \tag{11}$$

In the equation (4) to calculate the Reynolds number by the liquid, the equivalent diameter of a tubular-ball packing entering it, is defined [15] by the formula:

$$d_{ekv} = \frac{2 \cdot m \cdot \left[12 \cdot t_r \cdot t_b - \pi \cdot (6 \cdot d_{tr}^2 + n_1 \cdot n_2 \cdot d_{sh}^2)\right]}{3 \cdot \pi\left(m \cdot d_{tr} + d_{sh}\right)} \tag{12}$$

In this formula:

the relative height is $h = n_1 \cdot d_{sh}$. The amount of balls is $h/d_{ш} = n_1$;

the relative width is $в = (t_r + d_{tr}) = n_2 \cdot d_{sh}$. The amount of balls is $(t_r + d_{tr})/d_{sh} = n_2$;

the relative layer length *l*.

The hydraulic resistance of the irrigated ball packing weighted layer consists of the resistance of the balls and the liquid retained by them:

$$\Delta P_{PN} = \left(1-\varepsilon_{sh}\right)\cdot \rho_n \cdot g \cdot H_{st} + k_S \cdot \rho_l \cdot h_l \qquad (13)$$

Where k_S – adjusting coefficient. For the apparatus with a tubular-weighted packing $k_S = 0.558$; for the apparatus with a tubular-flowing packing $k_S = 0.65 \cdot S_{ap} / S_k$; h_l – the amount of the liquid retained by the weighted-ball packing.

CONCLUSION

Thus, the analysis of the operation of the apparatus with a movable packing and regular arrangement of packed elements in the contact zone volume allowed create designs of apparatus with a combined regularly weighted packing, combining positive qualities of analogues.

The research results of the hydraulic resistance of the apparatus with a regular structure tubular packing and with a combined regularly weighted packing were compared. Depending on the gas flow velocity for the apparatus with a regular structure tubular packing, the presence of three hydrodynamic modes (film-drop, drop, and drop entrainment) is noted. For the apparatus with a combined regularly weighted packing, four hydrodynamic modes (stationary state of the packing, transient mode, mode of developed turbulence, and drop entrainment) were defined.

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