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Calculation of Hydrodynamic Characteristics of Apparatus with Regular Tubular Packing

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Abstract: Among the apparatuses with a regular arrangement of packing elements creating an in-phase mode of vortex interaction, which ensures high efficiency of the processes, it is interesting to use a standard tubular packing. Such packing allows additional advantages associated with heat supply or extraction directly in the contact zone of the interacting phases, which is very important for conducting some chemisorption processes. The research covers such hydrodynamic regularities as hydraulic resistance during a heat carrier movement in pipes and during external flow around a tubular beam, retained liquid amount and gas content of layer in the external flow around the tubular beam with liquid and gas flows. The research was carried out using an experimental setup with a heat and mass transfer apparatus with regular tubular packing. The medium used during experiments is water-air. The research methodology included standard methods for determining hydraulic resistance and retained liquid amount and visual observation and photographing of gas-liquid flows. The novelty of the research was equations – one for calculating the hydraulic resistance in pipes, taking into account local resistances and pipe roughness. The other ones for determining the pressure losses during the external flow around the tubular beam, the retained liquid amount, and the gas content of the layer, taking into account the vortex interaction of gas and liquid flows. Graphical and calculated dependences of the investigated hydrodynamic characteristics were obtained as a result of the conducted research of the hydraulic resistance during the heat carrier movement in the pipes, as well as the hydraulic resistance and the retained liquid amount during the external flow around the tubular beam with a change in the gas velocity and irrigation density. When the heat carrier flows in the pipes, the numerical values of the hydraulic resistance in the transient mode do not exceed 1.5 kPa, in the developed turbulence mode in the range of the Reynolds number from $1 \cdot 10^4$ to $6 \cdot 10^4$ ΔP varies from 1.5 to 53 kPa. With the external flow around the tubular beam, in the developed turbulence mode w_g = 4 m/s and L = 25 m^3/m^{2}h, the hydraulic resistance is 85 Pa, the retained liquid amount is $4.5 \cdot 10^{-3}$ m. The change in the irrigation density in this mode (developed turbulence) in the L range from 10 to 100 m^3/m^{2}h leads to an increase in the hydraulic resistance from 65 to 160 Pa, the retained liquid amount from $2.16 \cdot 10^{-3}$ to $13.6 \cdot 10^{-3}$ m. The calculated dependencies are the basis of the method for calculating the hydrodynamic characteristics of the apparatus with the regular tubular packing, which can be used to calculate industrial devices.

Keywords: regular tubular packing, vortex interaction, local resistance, roughness, hydraulic resistance, retained liquid amount, gas content

1. Introduction

Packed apparatuses are widely used in chemical technology, petrochemistry, and oil refining during absorption, rectification, extraction, etc. (Lapteva 2019, Kagan et al. 2013). These apparatuses use stationary irregular and regular packing as contact elements (Laptev et al. 2017). Irregular packings (Raschig rings, Pall rings, Berl saddles, HY-PAK, CASCADE-RINGS, Inzhekhim packings) (Lapteva 2019, Laptev et al. 2017) increase hydraulic resistance, have relatively low efficiency, and are not able to work with contaminated gases and liquids. Regular packings (INTALOX, Sulzer, Koch, Inzhekhim, Norton, Vakupak, Glitch-Grid, Mellapak, MellapakPlus, Mellagrid, mesh packings BX and CY) contain channels of a regular structure. Therefore, they have slightly lower hydraulic resistance and higher performance indicators (Lapteva 2019). However, they are prone to overgrowth with solid deposits.

So there are many heat and mass exchangers with regular packing, the operation of which is based on the vortex interaction of gas and liquid flows (Einstein et al. 2002). Moreover, it is known that apparatuses with a regular arrangement of packing elements have proven themselves well in the absorption and dust collection processes in the production of phosphorus and chromium compounds due to low hydraulic resistance and relatively high efficiency (Volnenko 1999, Serikuly et al. 2020).

It is of interest to use regular tubular packing to carry out the heat transfer and the combined processes of heat transfer and mass transfer. Its functional area is a series of horizontal layers in height from regularly arranged pipes with fixed steps (distances) between the pipes in the vertical and radial directions.

The pipe mouth and orifice are equipped with collectors set on the outside of the body. The heat carrier overflows from the upper layer of the regularly arranged pipes through the collector bends. During operation, the spray from the irrigator does not mix with the heat carrier moving inside the pipes (Volnenko et al. 2013).

The use of tubular packing provides additional advantages associated with the heat supply or extraction directly in the interacting phases' contact zone, which is essential when carrying out some chemisorption processes.

The literature contains limited information on the research results of the hydrodynamic laws of regular tubular packing, which hinders the use of such apparatuses in industry.

The article presents research results on the main hydrodynamic characteristics of a liquid flow in the pipes and the external flow around the tubular beam in an apparatus with regular tubular packing. Also, to obtain the calculated dependences of the hydraulic resistance, the retained liquid amount, and the gas content of the layer for engineering calculations.

The research methodology includes standard methods for determining hydraulic resistance and retained liquid amount and visual observation and photographing of gas-liquid flows.

2. Experimental setup and research technique

An experimental setup was created to study the main hydrodynamic characteristics of the apparatus with regular tubular packing. Its technological diagram is shown in Fig. 1.

The airflow blown by fan 1 enters through the collecting tank into the apparatus column 10 (cross-section of 340x340 mm and a working area height of 1.3 m). Then, it passes through the tubular beam 8, rinsed with a liquid entering through the irrigator 7, and is released into the atmosphere. The airflow rate is regulated by gate 2 according to the readings of a standard diaphragm with a differential pressure gauge. The irrigation liquid from the lower container of apparatus 10 through the intermediate container 9 is supplied by pump 3 to pressure container 5, from which it is fed through the irrigator 7 for irrigation. The water flow rate is regulated by valve 6 according to the readings of a rotameter.

The technological scheme supplies the heat carrier to the pipe space in a closed circuit, including pump 3, the pressure container 5 with heater 4, and the tubular beam 8.

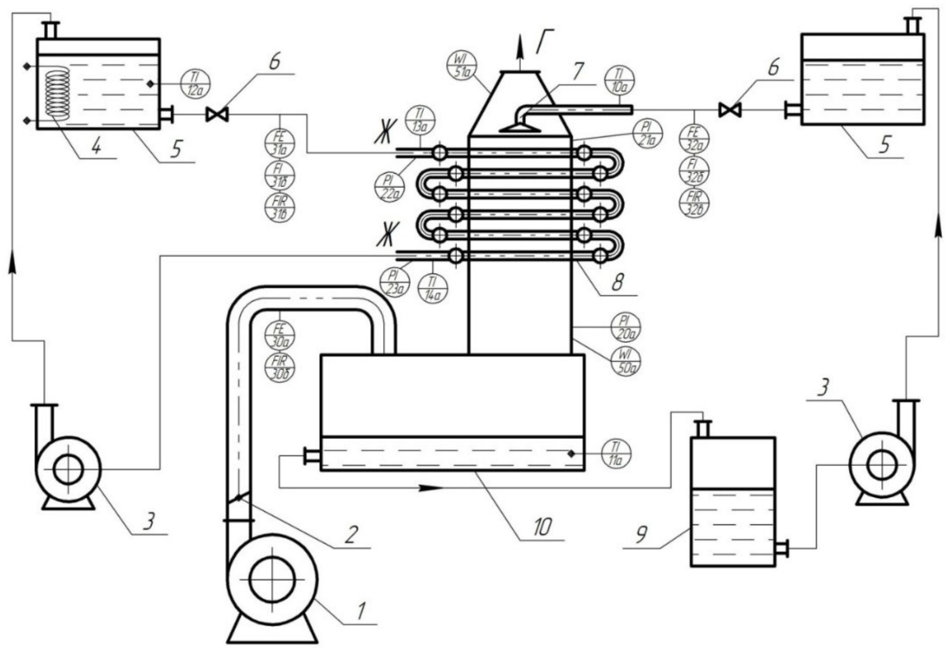

Fig. 1. Technological diagram of the experimental setup for determining the hydrodynamic characteristics of the apparatus with a tubular packing 1 – fan; 2 – gate; 3 – pump; 4 – heater; 5 – pressure container; 6 – valve; 7 – irrigator; 8 – tubular beam; 9 – intermediate container; 10 – apparatus with a tubular packing

Fig. 1 also shows the points where the gas flow rates, spray, heat carrier, pressure, temperature, and liquid level are measured.

The equipment used during studies is an apparatus with regular tubular packing (Fig. 2) (Volnenko et al. 2013), including an irrigated tubular beam, where the pipes are evenly spaced in vertical and radial directions with specific steps. In the vertical direction, a corridor arrangement of pipes is adopted. On the outer side of the apparatus body, the ends of the outgoing pipes are layer-by-layer connected to liquid collectors and a fitting for overflowing liquid to the downstream row. One of the collectors has a branch pipe for supplying liquid, and on the opposite side, a branch pipe for draining it.

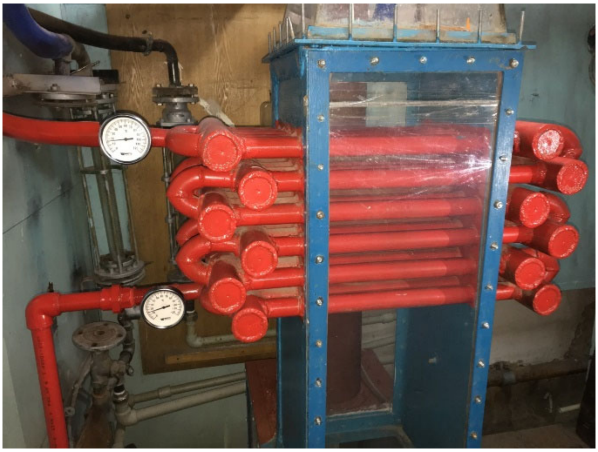

Fig. 2. The fragment of the working area of the apparatus with the regular tubular packing

The range of operating and design parameters of the hydraulic resistance and the retained liquid amount during the study on the external flow around the tubular beam is given below.

Operating parameters:
- gas velocity W_g – 1-5 m/s,
- irrigation density L – 10-75 $m^3/m^2 \cdot h$,
- air temperature t_{air} – 20-100°C.

Design parameters:
- step between the pipes in the vertical direction t_v/d – 2,
- step between the pipes in the radial direction t_r/d – 2,
- the pipe size: d = 0.025 m; ℓ = 0.34 m.

When the heat carrier flows in the pipes:
- liquid velocity w_l – 0.5-3.5 m/s (Re_l = 9000-70000),
- heat carrier temperature t_l – 16-100°C.

The hydraulic resistance of the apparatus *ΔP* was measured by a differential pressure gauge and controlled by a DSR-type device.

The retained liquid amount, referred to as the section of the column h_0, was determined by the "cut-off" method (Ramm 1976, Idelchik 1992). For this, the gate on the gas path and the valves on the irrigation liquid supply were simultaneously closed (Fig. 1). The retained liquid amount was determined using measuring containers.

3. The research results and calculated dependences

The research of the hydrodynamic characteristics was carried out for two cases. In the first case, the hydraulic resistance was determined during the heat carrier flow in the pipes. In the second case, the hydraulic resistance and the retained liquid amount were determined during the external flow of liquid and gas around the tubular beam.

For the first case, when the heat carrier flows in the pipes, hydraulic calculation of resistances determined by the pressure losses is complicated due to friction and local resistances.

Fig. 3 shows a graph of the dependence between tubular beam's hydraulic resistance ΔP and the Reynolds number Re_l.

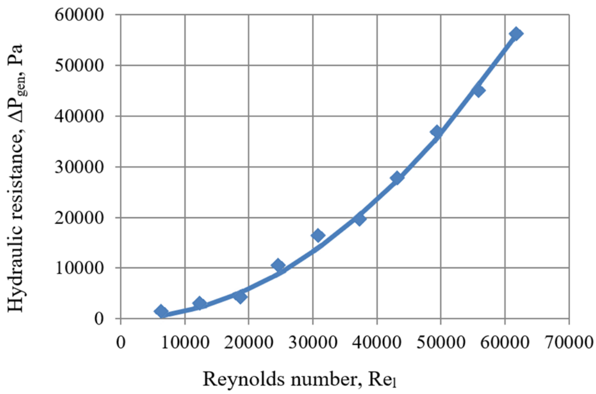

Fig. 3. The tubular beam's hydraulic resistance ΔP vs. the Reynolds number Re_l

The graph shows that liquid flows in the tubular beam in a transient mode ($2300 < Rel < 10000$) and a mode of developed turbulence ($Rel > 10000$). Within the whole range of Reynolds numbers, a steady increase in the hydraulic resistance is observed. Obviously, with an increase in the liquid flow velocity, the flow energy consumption for overcoming local resistance and friction resistance increases.

The total resistance of the pipe space is calculated based on the heat carrier movement pattern from the entry to the tubular beam to its exit. Fig. 4 shows the tubular beam and indicates the places of local resistance and friction resistance.

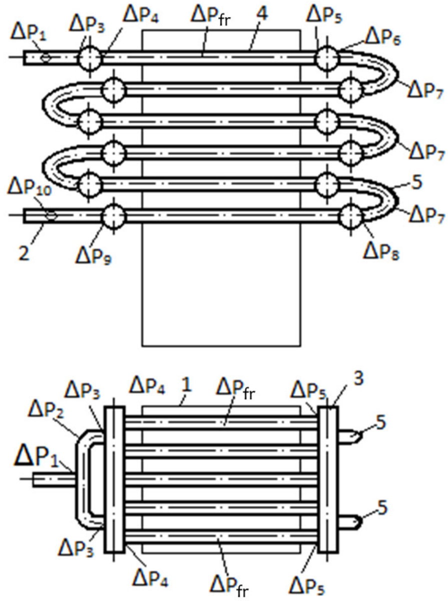

Fig. 4. Calculation of the hydraulic resistance of the tubular beam: 1 – body; 2 – tee; 3 – collector; 4 – pipes; 5 – branches; Δp_1 – pressure loss in the tee, Pa; Δp_2 – pressure loss in the elbow, Pa; Δp_3 – pressure loss at the split flow exit to the collector, Pa; Δp_4 – pressure loss at the flow exit from the collector to the beam pipes, Pa; Δp_{fr} – friction pressure loss in the heat exchanger pipes, Pa; Δp_5 – pressure loss at the flow entry from the pipes to the collector, Pa; Δp_6 – pressure loss at the flow exit from the collector to the branches, Pa; Δp_7 – pressure loss at the liquid movement along the branches, Pa; Δp_8 – pressure loss at the flow entry from the branches to the collector, Pa; Δp_9 – pressure loss at the flow entry from the collector to the tee pipes, Pa; Δp_{10} – pressure loss at the flow entry from the tee to the pipe, Pa.

The structure of the equation for calculating the hydraulic resistance depends on the route configuration in which the heat carrier flows. For our case of the heat carrier flow (Fig. 3), the structure of the equation for calculating the hydraulic resistance has the following form:

$$\Delta p = \Delta p_1 + (z-2)\cdot\Delta p_2 + z\cdot(\Delta p_3 + \Delta p_4 + \Delta p_{fr} + \Delta p_5) + \\ (z-1)\cdot(\Delta p_6 + \Delta p_7 + \Delta p_8 + \Delta p_9) + \Delta p_{10}, \quad (1)$$

where:
z – number of strokes in the tubular beam. The error between the calculated values and the experimental data is ± 9%.

The pressure loss in local resistances is calculated using the following formula:

$$\Delta p_i = \zeta_i \left(\frac{\rho \cdot w_i^2}{2}\right), \qquad (2)$$

where:
ζ_i – local resistance coefficient in the considered area of the heat exchanger (index i = 1, 2, ..., n) (Idelchik 1992);
w_i – liquid velocity in a narrow section of the considered area, m/s.

Friction pressure loss in the heat exchanger pipes (Domansky et al. 1982):

$$\Delta p_{fr} = \lambda_{fr} \frac{l}{d_v} \frac{\rho w_{fr}^2}{2}, \qquad (3)$$

where:
λ_{fr} – friction coefficient,
l – pipe length, m,
d_v – internal pipe diameter, m,
ρ – liquid density, kg/m^3,
w_{fr} – liquid velocity in the pipes, calculated from the area of the free section of one stroke, m/s.

The friction coefficient λ_{fr} depends both on the flow mode and on the roughness of the pipes or channels walls.

During turbulent flow, the friction coefficient substantially depends on the pipe wall roughness. The value λ_{fr} can be calculated using the formula (Domansky et al. 1982):

$$\lambda_{fr} = 0{,}11 \left(\frac{10}{Re} + 1{,}16 \frac{\Delta}{d_v}\right)^{0{,}25}, \qquad (4)$$

where:
Δ – pipe roughness, mm.

The hydraulic resistance and the retained liquid amount were studied in the external flow of liquid and gas around the tubular beam within the range of the operating parameters.

Balabekov & Volnenko (2015) summarize the research results of the hydrodynamic characteristics and parameters of mass transfer of various regular packing types (Balabekov et al. 2004, Balabekov 1984, Seitkhanov 2002, Bekibayev 2008, Yesskendirov, 2005, Sabyrkhanov, 1996, Kumisbekov 1999, Korganbayev 1999) (lamellar, cylindrical, prismatic with different crosssections, etc.). These results allowed to establish the patterns described in (Balabekov & Petin 2000, Balabekov et al. 2004). During flow around solids located regularly in the direction of flow, it is possible to achieve modes of simultaneous vortex formation (in-phase modes) when the time of formation and time of motion of vortices behind the chain of bodies coincides (Balabekov & Petin 2000). An increase in energy consumption accompanies this phenomenon.

For the apparatus with the tubular packing of a regular structure, the extreme points corresponding to the achievement of the simultaneous vortex formation modes are the steps of the pipes in the vertical direction $t_v/d = 2$ and 4 (Serikuly 2015, Serikuly et al. 2020).

When changing the steps of the arrangement of solids in the radial direction, another pattern was established (Balabekov et al. 2004). Up to the critical step between solids, the width of the gap between adjacent bodies determines the vortex formation size and frequency. Exceeding the crucial step leads to each solid forming vortices independently, and the solid width determines their frequency. The critical step in the radial direction for the tubular packing is $t_r/d = 2$ (Volnenko 1999, Serikuly 2015, Serikuly et al. 2020).

With the established steps of the pipe arrangement ($t_v/d = 2$ and $t_r/d = 2$), the studies of the hydraulic resistance and the retained liquid amount with a change in the operating parameters were carried out.

It is known that for most apparatuses with a regularly placed packing, when the gas flow velocity changes, the presence of three modes is characteristic: film-drop, drop and drop entrainment (Volnenko, 1999). At the same time, the most rational, in terms of the combination of energy consumption and the achieved efficiency, is the drop mode (gas velocity 2.5-4 m/s) (Volnenko 1999). The studies of the hydrodynamic characteristics are presented in Fig. 5 and 6.

Fig. 5 shows that an increase in the gas flow velocity causes an increase in the hydraulic resistance and the retained liquid. Due to the dynamic pressure increase, the hydraulic resistance rises along with the gas velocity increase. In this regard, the energy costs for overcoming the contact zone of the apparatus are growing. Furthermore, the dynamic pressure increase also contributes to the retention of more liquid in the packing volume.

The irrigation density increase (Fig. 6) leads to increased hydraulic resistance and the retained liquid. It is evident since more liquid is involved in the interaction process.

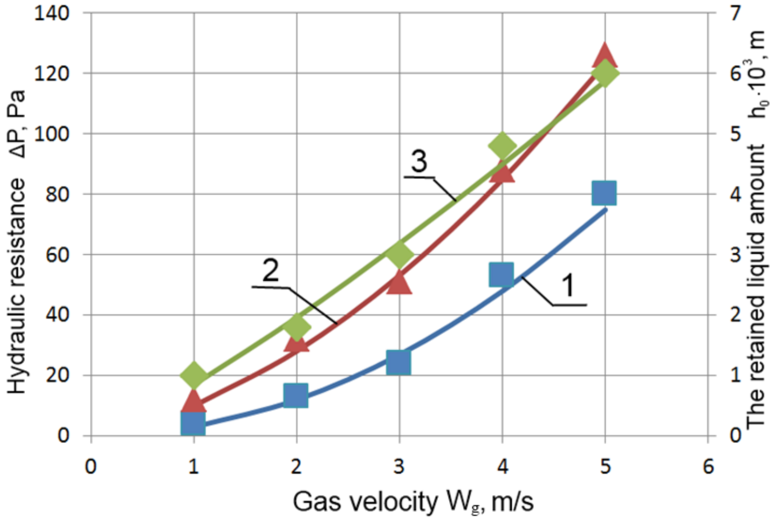

Fig. 5. Dependence of the hydraulic resistance ΔP_C, ΔP_L and the retained liquid amount h_0 on the gas velocity W_g; *Experimental conditions:* $t_v/d = 2$ *and* $t_r/d = 2$. $L = 25\ m^3/m^2h$; $1 - \Delta P_C$; $2 - \Delta P_L$; $3 - h_0$

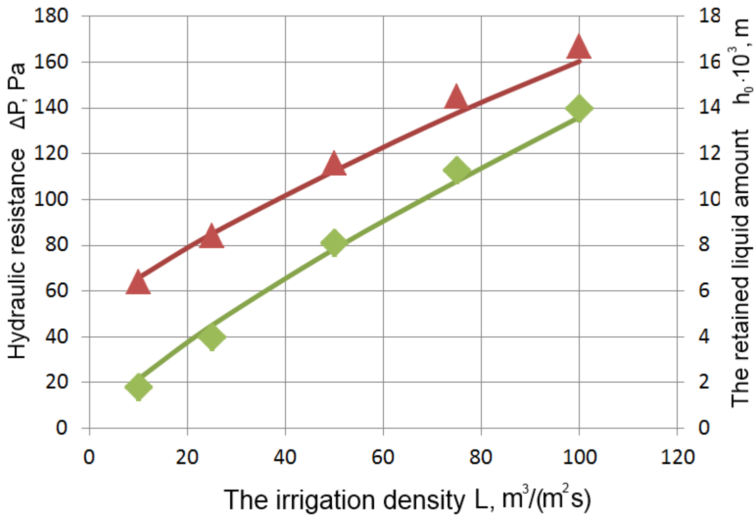

Fig. 6. Dependence of the hydraulic resistance ΔP_L and the retained liquid amount h_0 on the irrigation density *L: Experimental conditions:* $t_v/d = 2$ *and* $t_r/d = 2$. $W_g = 4\ m/s$; $1 - \Delta P_L$; $2 - h_0$

To calculate the hydraulic resistance of the apparatus without irrigation, including the flow pressure loss caused by the vortex formation and interaction in the tubular beam, the change in the gas flow direction, the friction of the gas against the packing elements' surface, the following dependence (Volnenko 1999) may be used:

$$\Delta P_c = \xi \cdot \frac{H}{t_v} \cdot \frac{\rho_g \cdot W_g^2}{2 \cdot \varepsilon_0^2}, \tag{5}$$

where:
H – packing area height, m,
ρ_g – gas density, kg/m^3.

The coefficient of resistance, taking into account the pressure loss during the vortex interaction in the vertical and radial directions, is calculated using the formula:

$$\xi = \mathrm{A} \cdot \theta_v \cdot \theta_r, \tag{6}$$

where:
A = 0,226 is a result of the processing of experimental data.

The following formula determines the porosity of the tubular packing:

$$\varepsilon_0 = 1 - \frac{d}{t_r} \tag{7}$$

The coefficient characterizing the vortex interaction degree in the vertical direction for the tubular packing elements θ_v (Balabekov & Volnenko, 2015):

$$\theta_v = 0{,}85 + 0{,}15\sin\left[\frac{\pi}{2}\left(\frac{4t_v \cdot S\ell}{m_k} + 1\right)\right], \tag{8}$$

where:
Sl – Strouhal number for the tubular elements, *Sl = 0,2*,
m_k – parameter that considers the vortex formation, the streamlined elements shape and the vortex velocity decrease.

For the tubular elements:

$$m_k = 0{,}44\left(1 - \exp(-t_v)\right) \tag{9}$$

The coefficient characterizing the vortex interaction degree in the radial direction and taking into account the change in the vortex formation frequency, θ_r can be determined by the formula (Balabekov & Volnenko, 2015):

$$\theta_r = \frac{\mathrm{t_r} - \lambda}{\mathrm{t_r} - d}, \tag{10}$$

Pulse elements located in the same row perpendicular to the streamlined flow contribute to the vortex formation with the scales λ. There are two cases for discretely located bodies in one row, perpendicular to the streamlined flow: at $t_r > 2d$ $\lambda = d$; at $t_r < 2d$ $\lambda = t_r - d$.

The error between the calculated values (using formula (5)) and the experimental data is ± 12%.

The hydraulic resistance of the irrigated packing, taking into account the flow pressure loss caused by the gas friction against the surface of the packing elements and the liquid film, can be calculated using the following dependence:

$$\frac{\Delta P_L}{\Delta P_c} = 1 + B \cdot \left(\frac{L_m}{G_m}\right)^{0,8} \cdot \left(\frac{\rho_g}{\rho_l}\right)^{0,4}, \tag{11}$$

where:
B = 8,5 – experimental coefficient. The error between calculated values and experimental data is ± 14%.

The mass flow of the gas (kg/s):

$$G_m = W_g \cdot S_{ap} \cdot \rho_g \tag{12}$$

The mass flow of the liquid (kg/s):

$$L_m = \frac{L}{3600} \cdot S_{ap} \cdot \rho_l \tag{13}$$

The retained liquid amount may be calculated using the balance equation:

$$\Delta P_L - \Delta P_C = \rho_l \cdot g \cdot h_0 \tag{14}$$

After substituting the hydraulic resistances of dry and irrigated apparatuses:

$$\xi \frac{H}{t_v} \cdot \frac{\rho_g W_g^2}{2\varepsilon_0^2} \cdot 12{,}4 \left(\frac{L_m}{G_m}\right)^{0,8} \cdot \left(\frac{\rho_g}{\rho_l}\right)^{0,4} = \rho_l \cdot g \cdot h_0 \,, \tag{15}$$

the retained liquid amount h_0 is obtained in the following form:

$$h_0 = \mathrm{C} \cdot \xi \cdot \frac{H}{t_v \cdot g} \cdot \left(\frac{W_g}{\varepsilon_0}\right)^2 \cdot \left(\frac{L_m}{G_m}\right)^{0,8} \cdot \left(\frac{\rho_g}{\rho_l}\right)^{1,4}, \tag{16}$$

where:
C = 5,06 – experimental coefficient. The error between the calculated values and the experimental data is ± 15%.

The gas content in the layer is determined by formula (Balabekov & Volnenko, 2015, Volnenko & Balabekov, 2016):

$$\varphi = \varepsilon - \frac{h_0}{H} \quad (17)$$

The following formula determines the volumetric porosity of the tubular packing in equation (17):

$$\varepsilon = 1 - \frac{\pi d^2}{4t_r \cdot t_v} \quad (18)$$

The novelty of the results presented in this article is the obtained experimental data of the hydrodynamic characteristics in various forms. First of all, graphical dependencies. Then, the calculated equations of the hydraulic resistance during the heat carrier flow in the pipes, the hydraulic resistance during the external flow around the tubular beam, the retained liquid amount and the gas content in the layer.

4. Conclusions

The laboratory setup was created and the research methods were selected to examine the main hydrodynamic characteristics of the apparatus with a regular tubular packing – the hydraulic resistance (when the liquid flows in the pipes and at the external flow around the tubular beam) and the retained liquid amount.

The research results of the hydraulic resistance in the pipes, the pressure loss during the external flow around the pipes and the retained liquid amount in the apparatus with a regular tubular packing with the change in the gas velocity and the irrigation density were obtained. It was noted that with the gas flow velocity increase, its dynamic pressure grows, and therefore, the hydraulic resistance and the retained liquid amount increase. Furthermore, the irrigation density increase also causes an increase in the hydraulic resistance and the retained liquid amount. The reason for that is the increase in the fluid volume involved in the interaction with the gas.

The equation for calculating the hydraulic resistance in the pipes is proposed. It takes into account the local resistances and the pipe roughness. The formulas for determining the pressure loss during the external flow around the tubular beam, the retained liquid amount, and the gas content in the layer take into account the vortex interaction between the gas and liquid flows.

The calculated dependencies (hydraulic resistance in the pipes, hydraulic resistance in the external flow around the tubular beam, retained liquid amount, gas content in the layer) are the basis for the calculation method of the hydrodynamic characteristics of the apparatus with the regular tubular packing. Such a method may be used to calculate industrial devices.

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