ABSTRACT

of dissertation for the degree of Doctor of Philosophy (PhD)
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Design and calculation of heat and mass transfer device with a complex regularly weighed nozzle

The dissertation research actuality. Apparatus with a movable packing (suspended and flowing) have become widespread in industry due to the simplicity of design and insensitivity to contamination of a gas-liquid medium with solid impurities. However, their significant drawback is significant hydraulic resistance, the main share of which is energy consumption for lifting the packing elements and maintaining them in suspension.

With the regular placement of the packing elements on the strings in the contact zone volume, the hydraulic resistance is significantly reduced and at the same time, due to the implementation of adjustable vortex interaction, the processes are significantly intensified.

At the same time, when carrying out dust collection processes with dust particles with enhanced adhesive properties, fine particulate matters precipitate on the packing elements and the apparatus walls, resulting in overgrowth of the packed layer, leading to the common mode disruption, and, consequently, to significant reduction in the effectiveness of ongoing processes.

To carry out such processes effectively, apparatus designs with combined regularly-suspended packing were created that allow using the advantages of the vortex interaction of flows in the regular packing layer with mechanical cleaning of deposits during the chaotic movement of suspended discrete contact elements. However, research results of such apparatus are not available.

In this regard, research, development of methodology for calculating and designing the apparatus with combined regularly-suspended packing in relation to the processes of mass transfer, contact heat transfer, and dust collection, recommendations for their design and operation are relevant.

The research subject was hydrodynamic laws, processes of mass transfer, contact heat transfer, and dust collection.

The objective of the work: development of scientific foundations of mass transfer, contact heat transfer, and dust collection processes in the apparatus with combined regularly-suspended particle, creation of scientifically-based methods for their calculation and design, and testing of the results in pilot industrial conditions with implementation in industry.

The scientific novelty of the research:

- assuming that gas flow in the packing volume is carried out through winding channels, calculated dependencies were obtained for determining the specific surface of the tubular-ball packing (tubular-suspended and tubular-flowing), their volume porosity, and also equivalent diameter;

- based on the revealed laws of gas and liquid flows' vortex interaction in the regularly-suspended packing volume, equations were obtained for calculating the hydraulic resistance, amount of retained liquid and gas content of the layer;
- using the theory of local isotropic turbulence and using the dissipative approach, an equation was obtained for determining the average drop diameter;
- using the single mechanism of vortex flow around solids and flow of phases through large plate openings, a frequency behavior was obtained that relates the frequency of liquid stream when the liquid film disintegrates from the tubular element with the frequency of vortex separation arising from the flow around the tubes;
- using the approach based on the analogy between friction and mass transfer, an equation was obtained for determining the mass transfer coefficients in the gas phase at low gas flow rates. At increased gas rates under bubbling conditions, an equation was obtained for calculating the mass transfer coefficients in the gas phase based on the surface renewal model;
- based on the analogy of heat and mass transfer processes at low and high gas flow rates, equations were obtained for calculating the heat transfer coefficients;
- based on the model of turbulent-diffusion deposition of solids, a formula was obtained for calculating the turbulent diffusion coefficient, which is used to determine the dust collection efficiency.

The theoretical significance of the research lies in the fact that, based on theoretical and experimental studies of the laws of vortex interaction of flows, a methodology was scientifically substantiated for calculating the apparatus with combined regularly-suspended packing for carrying out the processes of mass transfer, contact heat transfer, and dust collection.

The practical value. The apparatus design protected by the patent of the Republic of Kazakhstan for utility model № 3356 was developed.

Calculation methods, recommendations for the design and operation of the apparatus with combined regularly-suspended packing for carrying out the processes of mass transfer, contact heat transfer, and dust collection were developed.

Publications on the research issue. On the dissertation topic, 21 articles were published, of which 16 articles in the materials of international conferences, 1 article in the issue included in international database of scientific journals SCOPUS, 4 articles in the journals recommended by the Committee for Control in Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan, 1 patent of the Republic of Kazakhstan for utility model was obtained. The content of the articles covers the main content of the dissertation.

Introduction gives assessment of the current state of the scientific problem being solved, the basis and initial data for the development of the topic, the rationale for the need for research work, information on the planned scientific and technical level of development and metrological support of the dissertation, the actuality and novelty of the topic, the relationship of this work with other scientific research works, the research objective, object and subject, methodological base, provisions to be defended, practical value and practical testing results.

The first section analyzes the operation of the apparatus with weighted and regular movable packing in the processes of mass transfer, contact heat transfer, and dust collection, as well as methods for their calculation. Based on the analysis, the research tasks were formulated.

The second section describes experimental setups for studying hydrodynamic parameters, heat and mass transfer characteristics and dust collection, as well as experimental techniques.

The range of variation of operational parameters in the research: gas rate $w_г$ - 1÷5 m/s; irrigation density L -10÷75 $m^3/m^2 \cdot h$; air temperature $t_{возд.}$= 20÷100°C; heat carrier temperature in a hollow beam $t_ж$=16÷100°C; design parameters: vertical pitch between tubes $t_в/b$ - 4; horizontal $t_р/b$ - 2; tubular element size: d = 0,025 m; ℓ = 0,34 m; ball size: $d_ш$ = 0,015 m; static layer height: $H_{ст}$ = 0,015÷0,03 m; support distribution grid (free section): plain S_0>0,95 m^2/m^2; pyramidal $S_к/S_{ап}$=0,28 m^2/m^2.

A description is given of the apparatus with combined regularly-suspended packing of two types: tubular-suspended and tubular-flowing packing, and an equation is obtained for calculating the equivalent diameter:

$$d_{экв} = \frac{2 \cdot m \cdot \left[12 \cdot t_p \cdot t_в - \pi \cdot (6 \cdot d_{тр}^2 + n_1 \cdot n_2 \cdot d_ш^2)\right]}{3 \cdot \pi \left(m \cdot d_{тр} + d_ш\right)} \qquad (1)$$

To study the laws of interaction of the gas and liquid phases in the contact zone of the combined regularly-suspended packing, the research of hydrodynamic parameters, visual observations, and photographing of the layer structure were carried out.

The research was carried out with unchanged design parameters of the tubular packing ($t_в/b$=4; $t_р/b$=2) for the plain and pyramidal support distribution grids in the absence of irrigation and when irrigation is applied: with one and two layers of the ball packing; with one lower support distribution grid and partitioned by several support distribution grids. It was found that the numerical hydraulic resistance indicators are significant and the use of partitioned apparatus with combined regularly-suspended packing can be economically justified if they are used to clean dust with enhanced adhesive properties. In this regard, further research has been carried out for apparatus with one lower support distribution grid.

With change in the gas flow rate, four hydrodynamic modes were noted: stationary state of the packing, transitional, developed turbulence, and drop entrainment.

To calculate the hydraulic resistance of the apparatus with combined regularly-suspended packing, the following equation is proposed:

$$\Delta P_L = \Delta P_{тр} + \Delta P_{пн}, \qquad (2)$$

in which $\Delta P_{\text{тр}}$ is determined by the well-known equation for the apparatus with regular movable packing. The resistance coefficient included in it is calculated by the formula:

$$\xi_L = 0,53 \cdot \theta_в \cdot \theta_p \cdot \mathrm{Re}_{ж}^{0,1} \quad (3)$$

The hydraulic resistance of the suspended layer of the irrigated ball packing is calculated by the formula:

$$\Delta P_{\text{ПН}} = (1 - \varepsilon_{\text{ш}}) \cdot \rho_{\text{н}} \cdot g \cdot H_{\text{ст}} + \text{к}_s \cdot \rho_{ж} \cdot g \cdot h_{ж} \quad (4)$$

where к_s – adjusting coefficient. For the apparatus with tubular-suspended packing $\text{к}_s = 0{,}558$; for the apparatus with tubular-flowing packing $\text{к}_s = 0{,}65 \cdot S_{\text{ап}} / S_{\text{к}}$.

In the general case, the amount of retained liquid and the gas content of the layer is calculated by the formulas:

$$h_0^{\text{общ}} = h_0^{\text{ВН(ФН)}} + h_0^{\text{тр}} \quad (5)$$

$$\varphi_{\text{общ}} = \varphi_{\text{тр}} \cdot \varphi_{\text{ВН(ФН)}} \quad (6)$$

The amount of retained liquid and the gas content of the layer are calculated according to the well-known equations for the apparatus with regular tubular packing.

The amount of liquid retained by suspended ball packing is determined by the formula:

$$h_{ж} = \frac{\rho_{\text{г}} \cdot W_{\text{г}}^2}{\rho_{ж} g Fr}, \quad (7)$$

in which the Froude number is:

$$Fr = \text{А} \left(\frac{W_{\text{г}}}{W_{ж}}\right)^{\text{a}} \cdot \left(\frac{H_{\text{ст}}}{d_{\text{н}}}\right)^{\text{в}} \left(\frac{\rho_{\text{н}}}{\rho_{ж}}\right)^{\text{c}} \cdot \text{B} \quad (8)$$

For the apparatus with tubular-suspended packing: A=0,0084; a=0,29; в=-0,25; c=0,1; B=1; for the apparatus with tubular-flowing packing: A=0,0033; a=0,43; в=-0,25; c=0,1; B=$\left(tg\frac{\alpha}{2}\right)^{0,15}$.

The gas content is:

$$\varphi = \frac{W_{\text{г}}}{\text{C} \cdot \sqrt{\frac{g}{\rho_{\text{г}}}[\rho_{ж} h_{ж} + (1 - \varepsilon_{\text{ш}})\rho_{\text{н}} H_{\text{ст}}] + W_{\text{г}}}} \quad (9)$$

Coefficient C: $\varphi_{\text{ВН}} \sim 0{,}043$; $\varphi_{\text{ФН}} \sim 0{,}065$.

At low gas flow rates (up to 3 m/s), the determining structural components are film thickness, jet rate and diameter, as well as drop diameter in the tubular packing. These components are calculated from the known dependencies for regular tubular packing. At increased gas flow rates (more than 3 m/s), the bubble diameter is decisive. For the area of stochastic change in the bubble shape $\mathrm{Re}_{п} \geq 1530$, the bubble diameter will be:

$$d_n = B_n \cdot \frac{\sigma^{3/4}}{g^{1/4} \rho_{ж}{}^{3/4} W_n}, \tag{10}$$

where B_n - experimental coefficient.

From the analogy of interaction of parallel vortex jets during the gas or liquid flow through the system of discrete sources located across it, the following frequency behavior is obtained:

$$\psi_{в} = \frac{w_{г}}{u_{стр} \cdot 2\pi \cdot \varepsilon_{тр}} \tag{11}$$

The third section presents the research results of heat and mass transfer characteristics of the apparatus with combined regularly-suspended packing depending on the operating and design parameters. At the same time, the analogy of change in the obtained curves with the curves of hydrodynamic parameters is noted.

With drop flow of liquid for calculating the mass transfer coefficients in the gas phase based on the analogy between friction and mass transfer, the following equation is obtained:

$$\beta_{гs} = 3{,}17 \cdot \xi_L \cdot \frac{U_{к}^{13/10} \cdot \rho_{ж}^{2/5} \cdot \nu_{г}^{5/6}}{d_{к}^{1/10} \cdot \sigma^{2/5} \cdot D_{г}^{1/3}} \tag{12}$$

The equation for calculating the mass transfer coefficients in the gas phase under bubbling conditions is obtained based on the surface renewal model:

$$\beta_{гS} = 15{,}6 / (1 - \varphi_{ТФ}^{0{,}75}) \cdot \frac{h_{ж}^{3/4} \cdot g^{1/4} \cdot \psi_{в}^{1/4}}{d_n} \cdot D_{г}^{1/2} \tag{13}$$

The heat transfer coefficients are calculated from the condition of maintaining the constancy of the ratio of heat and mass transfer coefficients (the Lewis analogy).

The fourth section presents the research results of the dust collection parameters of the apparatus with combined regularly-suspended packing depending on the operating and design parameters.

Based on the mathematical model of turbulent-diffusion deposition of solids, an equation is obtained for calculating the coefficient of turbulent diffusion and the efficiency of dust collection:

$$D_T = 0{,}177 \cdot \left(\xi_{\mathrm{L}}\right)^{1/3} \cdot (1 - \varepsilon_{общ})^{1/3} \cdot \left(\frac{H_{cm}}{d_{ш}}\right)^{1/3} \cdot \left(\frac{H}{t_B}\right)^{1/3} \cdot \left(\frac{\rho_{г}}{\rho_{ж}}\right)^{1/3} \cdot \left(h_0\right)^{-1/3} \cdot d_k^{4/3} \cdot u_{г} \cdot Stk \tag{14}$$

$$\eta = 3,0 \cdot \left(\frac{W_{г} \cdot d_{k}}{D_{т}} \right)^{-1/4} . \quad (15)$$

The fifth section provides recommendations on the design and implementation of the apparatus with combined regularly-suspended packing.

The design recommendations provide information on the selection of operational and design parameters.

According to the research results, a design of an industrial apparatus with a combined regularly-suspended packing was developed, which was introduced at Aktobe Chrome Compounds Plant JSC in the technological scheme for purifying gas emissions during oxidative firing of a mixture in the production of sodium monochromate. At the same time, the concentration of dust emissions was reduced and economic damage was reduced by 34.6 times.

The conclusion gives brief conclusions on the dissertation research results, the tasks' solution completeness assessment, recommendations and initial data on the specific use of the results are developed, the assessment of the technical and economic effectiveness of implementation and scientific level of the work performed in comparison with the best achievements in this field are given.