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Calculation of Hydrodynamic Characteristics of a Cyclonic-Vortex Apparatus

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ABSTRACT

The article is dedicated to analyzing the experimental data and the calculated equations for the newly created cyclonic-vortex apparatus with separate centrifugal and vortex mechanisms defended by the patent of the Republic of Kazakhstan. For this purpose the experimental plant was created and both standard and specific research methods were used. To calculate the hydraulic resistance and its components (inlet section, annular zone, outlet section) of the cyclonic stage, the amount of retained liquid and the gas content of the layer, the calculated dependences verified by the experimental data are proposed. The comparison of the energy consumption of the new apparatus and the combined inertial-turbulent apparatus close in design is made. The opportunity of using the results of the study as the basis of the engineering calculation methodis pointed out.

Key words:dust collection, absorption, centrifugal force, regular packing, vortex interaction, hydraulic resistance, amount of retained liquid, gas content

INTRODUCTION

In many industries, existing technological schemes for gas cleaning include stages carried out in separate apparatuses, or in one, combining several zones for various processes. One of the significant examples is the use of multi-turn cyclone separators with varying heights of gas outlet tube in paddy pouring stations [1]. At the same time, schemes with combined apparatuses are often preferred, due to their compactness and low material consumption. This is particularly relevant due to the longer life circle of such models which helps to lower the harmful impact of the electric waste on the planet's ecology [2]. Directly in the contact zones, mechanisms are used that are based on vortex motion and interaction. This fully applies to the operation of dust collectors with countercurrent swirling flows [3], heat transfer intensification on arrays of rectangular ribs with different surface roughness, perforations or protrusions on ribs [4] and inserts [5], as well as heat and mass transfer apparatuses and dust collectors with a regular movable packing, whose work is based on the vortex interaction of gas and liquid flows [6, 7].

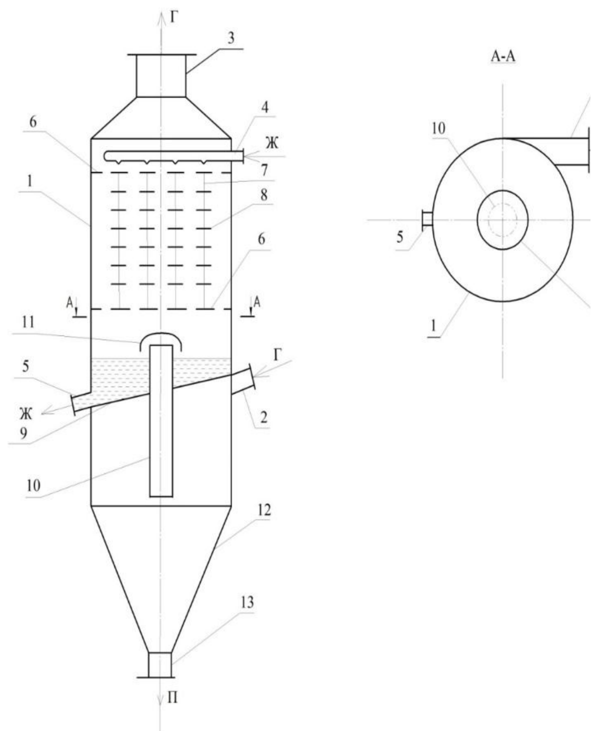
For separate carrying out of dust collection and absorption processes, the authors have developed the design of a cyclonic-vortex apparatus [6] with autonomous contact steps. In the lower contact stage, a centrifugal dust collection mechanism is used in the absence of irrigation with liquid, and in the upper contact stage, additive dust collection and absorption are carried out using the laws of vortex interaction of gas and liquid.

The purpose of the article is to analyze the results of studies of the main hydrodynamic characteristics of a cyclonic-vortex apparatus when changing operating parameters, compare with the results of other scientists in comparable conditions, and obtain calculated dependences.The research methodology included standard methods for determining hydraulic resistance and amount of retained liquid, as well as visual observation and photographing of gas-liquid flows.The research results allowed to obtain equations for calculating the hydraulic resistance, the amount of retained liquid and the gas content of the layer.

1. EXPERIMENTATION AND METHODOLOGY

The experimental plant for carrying out studies of hydrodynamic characteristics included a cyclonic-vortex apparatus, a fan, a pump, circulation and pressure tanks of liquid for irrigation of the upper contact stage, a container for collecting dry dust from the lower contact stage, a compressor for spraying dust at the inlet of the dust collector.

The studied object is a cyclonic-vortex apparatus (Figure 1) [8].



1 – casing; 2 – gas inlet pipe; 3 – gas outlet pipe; 4 – irrigator; 5 – fitting for draining the spent absorber; 6 – support-distribution grid; 7 – strings; 8 – packing bodies; 9 – inclined partition; 10 – central tube; 11 – cap; 12 – conical bottom; 13 – pipe for collected dust outlet

Figure 1: The cyclonic-vortex apparatus

The apparatus includes a casing 1, pipes 2 and 3, respectively, for gas inlet and outlet, an irrigator 4 for irrigation liquid inlet into the upper contact stage and a fitting 5 for draining the spent absorber, support-distribution grids 6, strings 7 with packing bodies 8 fixed to them. The upper and lower contact stages are separated by an inclined partition 9 with a central tube 10 mounted therein, located coaxially with a casing of the lower contact stage. The upper cut of the central tube is equipped with a cap 11. The lower contact stage has a conical bottom 12 with a pipe for collected dust outlet 13.

The gas flow entering for cleaning is supplied through the gas inlet pipe 2 installed tangentially in the lower part of the apparatus. When the gas flow is tangentially supplied, a centrifugal force arises which acts on the solid particles of dust, pressing them to the inner wall of the apparatus 1. Under the gravity action, the solid particles of dust slide into the conical bottom 12 of the lower contact stage and are removed from the apparatus through the pipe 13.

The dust-free gas flow through the upper cut of the central tube 10 enters the upper contact stage. At the entrance to it, the central tube 10 is equipped with the cap 11 to prevent the entry of flowing irrigation liquid.

The lower and upper contact stages are separated by the inclined partition 9, as a result of which their work occurs autonomously.

The operation of the upper contact stage takes place in countercurrent mode. In this case, the gas flow entering from below interacts with the irrigation liquid supplied through the irrigator 4 in the packing zone volume. The arrangement of the packing bodies 8 on the strings 7 is made with a step in the vertical direction, ensuring the achievement of the simultaneous vortex formation mode (in-phase mode).

The cleaned gas flow is discharged from the apparatus through the pipe 3, and the liquid spent in the upper stage is removed through the fitting 5.

The apparatus has the following structural dimensions: the apparatus diameter is 0.4 m; the total height is 3.9 m. The cyclonic part: the angle of inclination of the inlet pipe is 15°; the height is 1.825 m; the diameter of the exhaust pipe is 0.24 m. The packing part: the height of the packing zone is 1 m; the step between the packing elements vertically is 2b, horizontally is 2b; the size of the packing elements (plates) $b \times b \times \delta = 40 \times 40 \times 1$ mm.

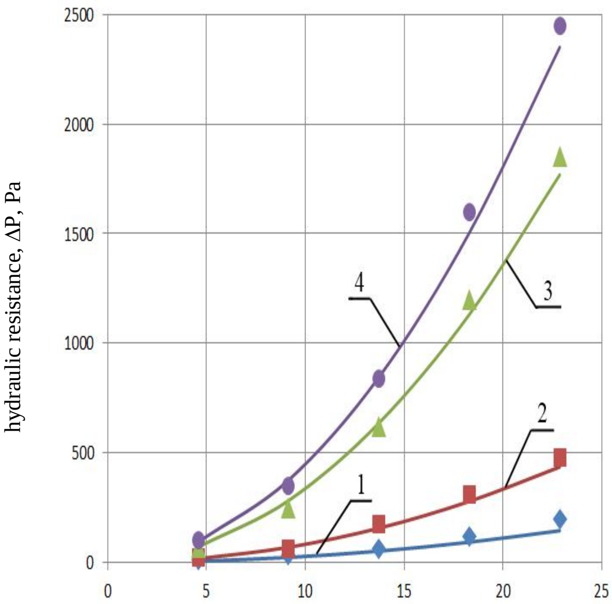
The hydraulic resistance of the apparatus ΔP was measured by a differential pressure gauge and controlled by an inclined micromanometer.

The amount of retained liquid, referred to the column cross section h0, was determined by the "cutoff" method [9]. For this, the gate valve on the gas path was blocked, and the valves for supplying the irrigation liquid were closed simultaneously. The amount of retained liquid was measured using measuring tanks.

2. RESULTS AND DISCUSSION

The main hydrodynamic characteristic of the apparatus' cyclonic stage is hydraulic resistance. The pressure sampling points were arranged on the gas inlet pipe, on the casing of the cylindrical part, on the casing of the central tube. By the pressure difference using a cistern-type manometer,the hydraulic resistance of the inlet section ΔP_{inl}, the hydraulic resistance of the annular zone ΔP_{ann}, the hydraulic resistance of the outlet section $\Delta P_{outl}$and the hydraulic resistance of the cyclonic stage ΔP_c were determined.

Figure 2 shows a graph of the hydraulic resistance of all components of the cyclonic stage.



Gas velocity in the inlet pipe W_{inl}, m/s
the curves – calculation; the points – experiment.
1 – ΔP_{ann}; 2 – ΔP_{outl}; 3 – ΔP_{inl}; 4 – ΔP_c.

Figure 2: The hydraulic resistance of the cyclonic stage components depending on the gas velocity in the inlet pipe

As can be seen from the graph, the hydraulic resistance of the cyclonic stage and all its components is increasing. This is obvious, since the increase in the hydraulic resistance with increasing the gas velocity is due to the increase in the dynamic pressure and losses associated with the change in the gas motion direction and friction losses.

The work [10] presents the results of calculating the hydraulic resistance of a cyclone when the gas velocity at the apparatus inlet changes according to the equations presented by various authors [11]–[13], as well as the data of the authors' studies obtained for the cyclonic stage. Additional general information on the gas mobility and absorption [14] was also of relevance. The comparative analysis showed that the calculated data according to the equations proposed in [11], [13] and the authors' data have close values, while the data in the work [12] are somewhat overestimated.

The apparatus' packing stage includes a contact zone in which lamellar contact elements are regularly arranged on the strings in the vertical and radial directions.

The results of numerous experimental studies [15]–[21], summarized in the monograph [6], indicate that such structural parameters as the shape of the packing elements, the distance (or dimensionless step) between the packing elements in the vertical and radial directions have a great influence on the hydrodynamic characteristics and dust collection parameters of the studied apparatuses.

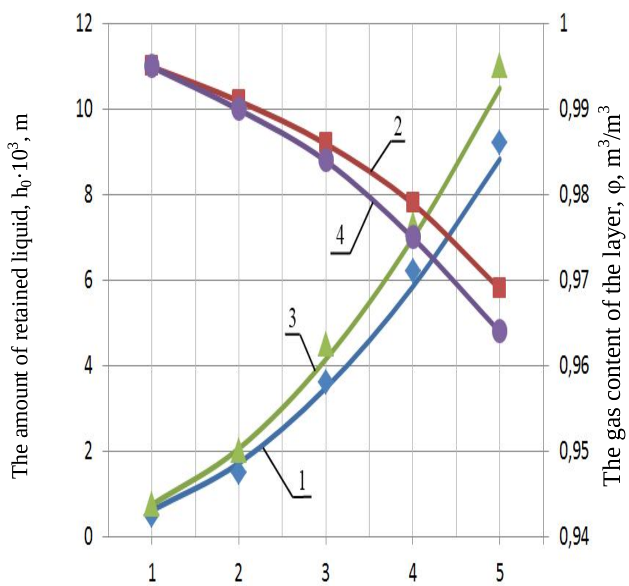
The analysis of the vortices' interaction mechanisms in the vertical direction behind the lamellar packing elements indicates the achievement of simultaneous vortex formation modes or in-phase modes with the arrangement steps tv = 2b and 4b. The achievement of the in-phase mode leads to the increase in energy consumption, however, the total power of the vortices contributes to more work on crushing the irrigating liquid, as a result of which the interphase surface increases and the ongoing processes are significantly intensified. The phenomenon of in-phase interaction of vortices is the basis of a scientific discovery [22].

The steps of arranging the packing elements in the radial direction have some critical value [23]. When distances between the packing elements are less than the critical (td<2b), the vortex formation frequency in the gap is determined by its size. When the step between the elements exceeds the critical value (td>2b), the vortex formation frequency determines the characteristic size of the elements in the mid-length section.For most streamlined packing elements and coarse hole plates, the critical step value is td=2b [6].

In connection with the foregoing, to carry out studies of the cyclonic-vortex apparatus, the next arrangement steps were taken for the plate-shaped packing elements in the vertical direction tv=2b, in the radial direction td=2b.

To establish the operating modes of the packing zone with the accepted arrangement steps of the packing elements, the hydraulic resistance was studied depending on the gas velocity at various irrigation densities [24].It was established that, like most apparatuses with a regular movable packing [6], the plate packing is characterized by three hydrodynamic modes: film-drop (the gas velocity is from 1 to 2.5 m/s), drop (the gas velocity is 2.5-4 m/s) and drop entrainment (the gas velocity is over 4 m/s).

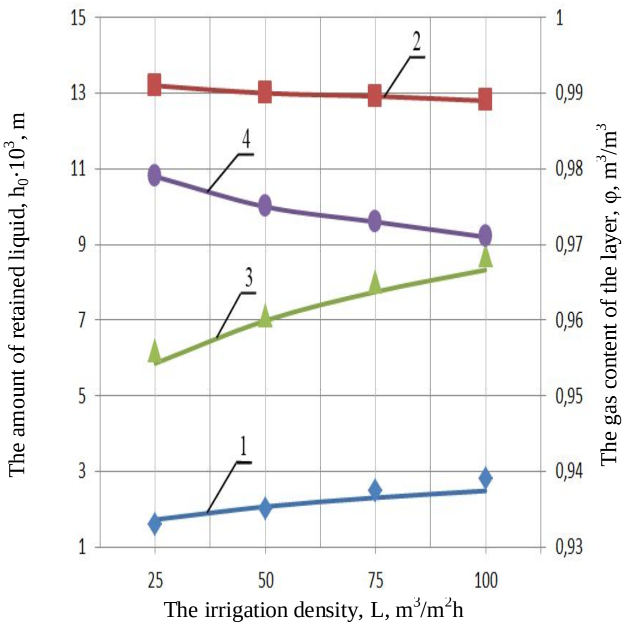
The research results of the amount of retained liquid h0 and the gas content of the layer φ depending on the gas velocity and irrigation density are presented in Figures 3 and 4.



The gas velocity,W_g, m/s

Experimental conditions: tv= 2b; td=2b; bxbxδ=40x40x1 mm. The curves – calculation; the points – experiment.1 and 3 – h0 andφat L=25 m3/m2h; 2 and 4 – h0 andφat L=50 m3/m2h

Figure 3: Dependenceof the amount of retained liquid h0 and the gas content of the layer φ on the gas velocity



Experimental conditions: tv= 2b; td=2b; bxbxδ=40x40x1 mm. The curves – calculation; the points – experiment.1 and 3 – h0 andφatWg =2 m/s; 2 and 4 – h0 andφatWg =4 m/s

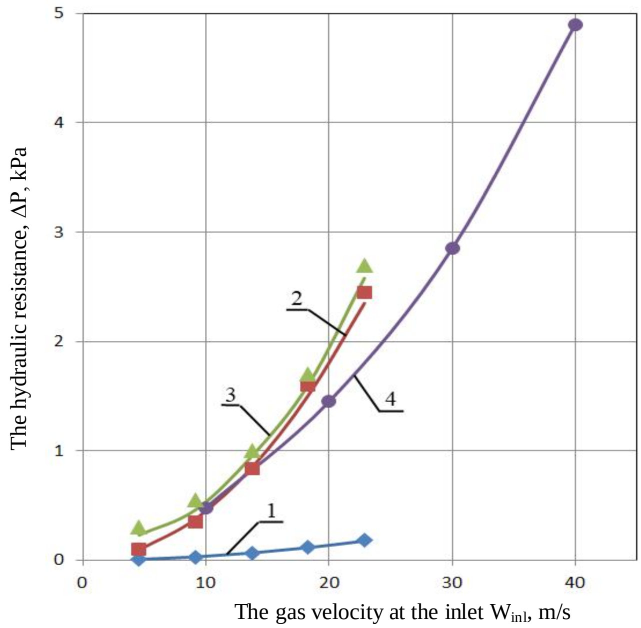
Figure 4: Dependence of the amount of retained liquid h0 and the gas content of the layer φ on the irrigation density

As can be seen from Figure 3, as the gas flow velocity increases, the amount of retained liquid increases. It is known that as the gas velocity increases, the dynamic pressure increases, and this helps to retain more liquid in the packing volume.

The calculated data on the gas content of the layer (Figure 3) show that with the increase in the gas velocity the values of these indicators decrease. This is due to the increase in the amount of retained liquid with a constant volume of the contact zone.

The graph of the amount of retained liquid and the gas content of the layer on the irrigation density (Figure 4) shows that the increase in the irrigation density contributes to the increase in the amount of retained liquid, while the calculated values of the gas content decrease slightly. This is obvious, since the influx of additional liquid volume increases and the time of its delay increases, and this helps to decrease the gas content.

Figure 5 shows the generalized research results of the hydraulic resistance of the apparatus' cyclonic and vortex stages, the total resistance of the cyclonic-vortex apparatus, as well as the hydraulic resistance curve of the combined inertial-turbulent apparatus (CITA) with autonomous irrigation circuits [25],[26].



Experimental conditions: tv= 2b; td=2b; bxbxδ=40x40x1 mm.1 – ΔPL at L=25 m3/m2h; 2 –ΔPr; 3 –ΔPapp; 2 –ΔPdc (CITA [22]).

Figure 5: Dependenceof the hydraulic resistance of the apparatus' cyclonic and vortex stages, the total resistance of the cyclonic-vortex apparatus and the dust collection zone of the CITA apparatus on the gas velocity in the inlet pipe

As can be seen from Figure 5, the hydraulic resistance of the apparatus' cyclonic and vortex stages, as well as the total resistance of the cyclonic-vortex apparatus on the gas velocity increase.

When analyzing the experimental data of the contact stages, it was noted that increase in the hydraulic resistance with increasing the gas velocity is due to increase in thedynamic pressure, increase in the energy consumption for overcoming local resistances and friction.

The graph (Figure 5) also shows the hydraulic resistance curve of the combined inertial-turbulent apparatus (CITA) with autonomous irrigation circuits [25]. A choice for the comparative analysis of the CITA is due to the fact that these apparatuses can be used in the dust collection and absorption processes, as well as from their structural analogy. The cyclonic-vortex apparatus and the CITA have two contact levels, separated by the partition, which ensures the autonomy of their operation. The upper contact stages are the packing zones with the regular movable packing. The difference is that in the CITA, the lower contact stage provides an impact-inertial dust collection mechanism, while in the cyclonic-vortex apparatus, a centrifugal dust collection mechanism is implemented.

The analysis of the curves (Figure 5) shows that at the gas flow velocities in the inlet pipe from 10 to 25 m/s, the hydraulic resistance values of the cyclonic-vortex and CITA apparatuses are comparable with some excess for the cyclonic-vortex apparatus. However, in the recommended range of the gas velocities in the pipe for the CITA 30-35 m/s, the hydraulic resistance, and, consequently, the energy consumption of the CITA significantly exceed the data obtained for the cyclonic-vortex apparatus.

The parameters characterizing the hydrodynamics of the cyclonic-vortex apparatus are the hydraulic resistance (of the cyclonic and packing zones), the amount of liquid retained in the packing zone and the gas content.

The hydraulic resistance of the cyclonic-vortex apparatus is determined based on the additivity of the resistance of the centrifugal force and the packing zone [27]:

$$\Delta Papp = \Delta Pc + \Delta PL, \quad (1)$$

whereΔPc–the hydraulic resistance of the centrifugal force coverage, Pa; ΔPL– the hydraulic resistance of the packing zone, Pa.

The hydraulic resistance of the cyclonic stage is determined by the equation:

$$\Delta P_c = \Delta P_{inl} + \Delta P_{ann} + \Delta P_{outl}, \quad (2)$$

where$\Delta Pinl$–the hydraulic resistance of the inlet section, Pa; $\Delta Pann$– the hydraulic resistance of the annular zone, Pa;$\Delta Poutl$– the hydraulic resistance of the outlet section, Pa.

The hydraulic resistance of the inlet section:

$$\Delta P_{inl} = \xi_{inl} \cdot \frac{\rho_г \cdot w_{inl}^2}{2}, \quad (3)$$

where$\xi_{inl} = 3{,}32$ – the gas inlet resistance coefficient; winl – the gas velocity at the inlet, m/s.

The hydraulic resistance of the annular:

$$\Delta P_{ann} = \xi_{ann} \cdot \frac{\rho_г \cdot w_{ann}^2}{2}, \quad (4)$$

where$\xi_{ann} = 4{,}1$ – the resistance coefficient when passing the annular gap; w_{ann} – the gas velocity in the annular gap, m/s.

The hydraulic resistance of the outlet section:

$$\Delta P_{outl} = \xi_{outl} \cdot \frac{\rho_г \cdot w_{outl}^2}{2}, \quad (5)$$

where$\xi_{outl} = 5{,}7$ – the gas outlet resistance coefficient; w_{outl}– the gas velocity at the outlet, m/s.

The hydraulic resistance of the packing zone is determined by the formula used to calculate apparatuses with the regular movable packing [6], [28],[29]:

$$\Delta P_L = \xi_L \frac{H}{t_в} \cdot \frac{\rho_г \cdot W_г^2}{2\varepsilon_0^2}. \quad (6)$$

Here, H–the packing zone height, m;ε_0–porosity of the packing:

$$\varepsilon_0 = 1 - \left(\frac{b}{t_p}\right)^2. \quad (7)$$

The resistance coefficient of the irrigated packing ξ_L takes into account the vortices' interaction degree in the vertical and radial directions, the pressure losses on the gas friction on the liquid surface [6]. By processing the experimental data, the next expression is obtained for determining ξ_L:

$$\xi_L = 0{,}7 \cdot \theta_в \cdot \theta_р \cdot \frac{\mathrm{Re}_ж^{0,25}}{\mathrm{Re}_г^{0,1}}, \quad (8)$$

Where RelandRer – the Reynolds numbers for gas and liquid; θvert and θrad– the coefficientsthat take into account the vortices' interaction degree in the vertical and radial directions.

The Reynolds number in the gas phase, which is determined by the formula:

$$\mathrm{Re}_g = \frac{W_г \cdot d_{экв}}{\nu_г}. \quad (9)$$

Where deqv– the equivalent diameter of packing, m.

The Reynolds number Relis determined by the formula:

$$\mathrm{Re}_l = \frac{U_ж \cdot d_{экв}}{\nu_ж}, \quad (10)$$

where $U_æ$ = L/3600 –the liquid velocity, m/s.

The equivalent diameter of the packing is determined as the equivalent diameter of the channels through which the gas moves:

$$d_{eqv} = \frac{2(t_в \cdot t_p^2 - b^2 \cdot \delta_н)}{b^2 + 2b \cdot \delta_н}. \quad (11)$$

To derive the calculated dependences of the amount of retained liquid (ARL) h0 and the gas content of the layer φ, the authors used the approach described in [16, 17, 30].

As a result, the next formula was obtained for calculating the amount of retained liquid:

$$h_0 = (h_{пл} + h_k) \cdot \frac{H}{t_в}, \quad (12)$$

Where $h_{пл}$–the conditional liquid height, which is in the form of a film on the packing elements of one row and referred to the cross section of the column, m;$h_к$–the drop component of the retained liquid coefficient in the row of packing elements formed above- and down located packing elements, m.

The film component of the retained liquid coefficient can be determined by the following dependence:

$$h_{пл} = \frac{\delta_{пл} \cdot b^2}{t_p^2}. \quad (13)$$

Here $\delta_{пл}$ – the liquid film thickness on the plates' surface, m.

Using the energy conservation equation, a formula is obtained for determining the drop component of the retained liquid coefficient:

$$h_k = 0,88 \cdot \xi_L \frac{\rho_г W_г^2}{2g\rho_ж} \cdot \frac{(2-\varepsilon_0)(1-\varepsilon_0^2)}{\varepsilon_0^2} \quad (14)$$

whereB_h=0.88 – the experimental coefficient.

The equation for calculating the gas content of the layer has the form:

$$\varphi = \varepsilon - \frac{h_0}{H} \quad (15)$$

The comparison of the experimental and calculated data obtained using standard functions showed that the error of equation (1) was ±15%, (2) ±9%, (6) ±12%, and (12) ±10%.

3. CONCLUSION

To carry out the studies of the hydraulic resistance and the amount of retained liquid of the cyclonic-vortex apparatus, the experimental plant was created and the research methods were selected.

When studying the hydraulic resistance of the cyclonic stage and its components (inlet section, annular zone, outlet section), it was noted that the increase in the hydraulic resistance with the increase in the gas velocity is due to the increase in the dynamic pressure and losses associated with the change in the direction of gas motion and friction losses.

When studying the hydraulic resistance, the amount of retained liquid and the gas content of the layer with the change in the gas velocity and the irrigation density of the apparatus' packing zone, three hydrodynamic modes were noted: film-drop, drop and drop entrainment. As the gas velocity increases, the dynamic pressure increases, and this helps to retain more liquid in the packing volume. With the increase in the irrigation density, the influx of the additional liquid volume increases and the time of its delay increases, and this helps to decrease the gas content. The comparison with the combined inertial-turbulent apparatus close in design with the autonomous irrigation circuits showed that under comparable conditions the energy consumption of the cyclonic-vortex apparatus is much lower.

To calculate the hydraulic resistance, the amount of retained liquid and the gas content of the layer, the calculated dependences are proposed, which are the basis of the engineering calculation method.

The experimental data and the calculated equations are obtained for the newly created apparatus, the design of which is defended by the patent of the Republic of Kazakhstan. The adequacy of the obtained equations was verified by the comparison with the experimental data. The error was 9-15%.

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