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HYDRODINAMICS MODELING OF GAS SEPARATOR INERTIAL AND FILTER ELEMENTS FOR NATURAL GAS FINE CLEANING

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Abstract. The trends in the development of modern gas separation equipment have been considered. On the basis of computer modeling the optimal size of the device has been obtained. Reasonable choice of a computer and mathematical experiments, as a research method has been shown. The experimental results of the double-circuit dust collector investigations have been represented.

Keywords: gas separation, modeling, inertial and filter elements, separation, gas-fluid system.

1. Introduction

Purification of gas emissions from chemical productions, as well as cleaning of natural and associated petroleum gases from the fluid (condensate, hydrate formation inhibitor, water) and mechanical impurities is a key problem of the present time. Therefore the gas-separation equipment is a required element at industrial enterprises of chemical and oil-gas refining plants [1, 2].

Variety of technological processes and the impact of many factors on the separation process cause an extraordinary diversity of plants equipment design. The following equipment is used for gas purification: vertical, horizontal, spherical, louvre and gauze gas separators; oil and multicyclone dust collectors; adsorbers and absorbers of different design [3].

Generally, the separation of heterogeneous systems can be classified by principles of gas separators operation: gravitational ones, where the dispersed phase deposits under the influence of gravity; inertial ones, with a continuous phase swirling in the same plane relative to exit points of the feed tube or holes; with a spiral flow swirling, equipped with louvre, gauze and fibrous nozzles, where fluid and solid dispersed particles deposit; centrifugal ones and their combinations.

Traditionally used low-effective gas separation methods and design of gas separators do not satisfy modern requirements (separation efficiency of gravity-inertial type separators does not exceed 70 % and sometimes it is only 30–40 %) [3].

Therefore the studies concerning gas separation technology improvement are topical now, because the requirements for the harmful substances content in emissions from chemical industrial enterprises, the quality of products and the degree of energy resources utilization are constantly increasing [1].

The aim of this work is to simulate the hydrodynamics of inertial and filter separation elements, to study the separation mechanism of high-dispersive gas-fluid systems, to determine the hydraulic resistance and to predict the efficiency of two-staged gas separator for natural gas fine cleaning.

As a result of the modern design analysis of gas separation devices, which are used in domestic and foreign technologies for the separation of solid particles and dropping fluid of specified fractional composition, it is technologically and economically feasible to apply the separation in few stages [4].

As the first separation stage it is efficiently to use the separation of fluid and solid particles in the field of centrifugal forces in cyclone type devices [5].

Cyclones are the most common type of mechanical devices for the separation of solid and fluid particles from a gas flow due to their low cost, simple construction and high productivity. Cyclones have the following advantages: absence of moving parts, reliable operation within a wide temperature range, the ability to operate under high pressures, the stable value of the hydraulic resistance, simplicity of manufacturing and the possibility of repairing works. The disadvantage is the relatively high hydraulic resistance (1250–1500 Pa) [3, 6].

Nowadays the study of equipment operation hydrodynamics is carried out in several stages. One of them is a computer simulation, *via* which it is possible to choose an optimal geometric configuration and process parameters, and make a physical model for the further studies.

2. Experimental

The operation of some high-effective gas separation devices (Fig. 1) was already experimentally investigated [3].

The investigations of hydrodynamics and estimation of operating characteristics of separators were carried out using physical (experimental) and mathematical (numerical) modeling on developed models and stands (Fig. 2). Physical experiment is carried out in accordance with main regulations of the similarity theory. Numerical modeling is based on classical concepts of fluid and gas mechanics, as well as main equations of hydrodynamics using computational fluid dynamics (CFD) and finite element methods (FEM). The modeling systems are: air–water (physical experiment) and natural gas–water–hydrocarbon condensate (computer simulation). The fluid/gas ratio (unit rate of flow, F/G) at the inlet of the gas separator varies from 0 to 0.20. The system geometrical parameters are: the diameter of the experimental-industrial gas separator D = 2200 mm; height H = 9000 mm (Fig. 1d); number of elements in multicyclone (1st stage of separation, drop catcher) N = 535 (lower row N_0 = 48, 1st row N_1 = 152, 2nd row N_2 = 170, 3rd row N_3 = 165); number of the cartridge filters in a filter-coalescer (2nd stage of separation, mist eliminator) N = 51; experimental sample of the multicyclone element with the diameter d = 89 mm and the height h = 320 mm, the diameter of exhaust manifold d_1 = 57 mm, swirler of a “rosette” type (number of blade n = 4, initial angle of attack α = 27°), the diameter of overflow pipe d_2 = 25 mm; cartridge element of the filter-coalescer with the diameter d = 170 mm and the height h = 1100 mm; the diameter of frame pipe d_1 = 120 mm.

The experimental plant (Fig. 2a) consists of lines for water and air; gas-meter for air supply; pipeline which acts as a spray chamber (it creates a fluid pneumatic dispersion); cyclone element; fibrous filter and gage vessel (receiving reservoir).

To measure the flow discharge and gas-dynamic resistance, total and static pressure at the inlet and outlet of the gas separator we provided the special units made of coaxial tubes of total and static pressure (Pito-Prandtl tubes). They are attached to a micromanometer with inclined tubes by impulse tubes. The investigated drop catcher (inertial stage) and mist eliminator (filtering stage) are consecutively attached in the experimental plant to estimate the operation efficiency. Due to the realignment of pipe lines it is possible to investigate the mentioned elements by turns.

For a detailed analysis of the hydrodynamic conditions of gas separation in cyclones we used the method of mathematical computer experiment. Hydrodynamic process of two-phase gas flow (gas, dropping fluid) which moves along 3D geometrical model of the separator inertial element was modeled considering the fact that the separation occurs under the gravitational and inertial forces. For practical application we used the complex of computer programs such as KOMPAS 3D and Fluent Flowizard. The advantages of such calculations are: to analyze in details the influence of cyclone structural elements on its hydrodynamics; to carry out virtual testing of several variants of separators without their manufacturing and laboratory analysis; to optimize the design.

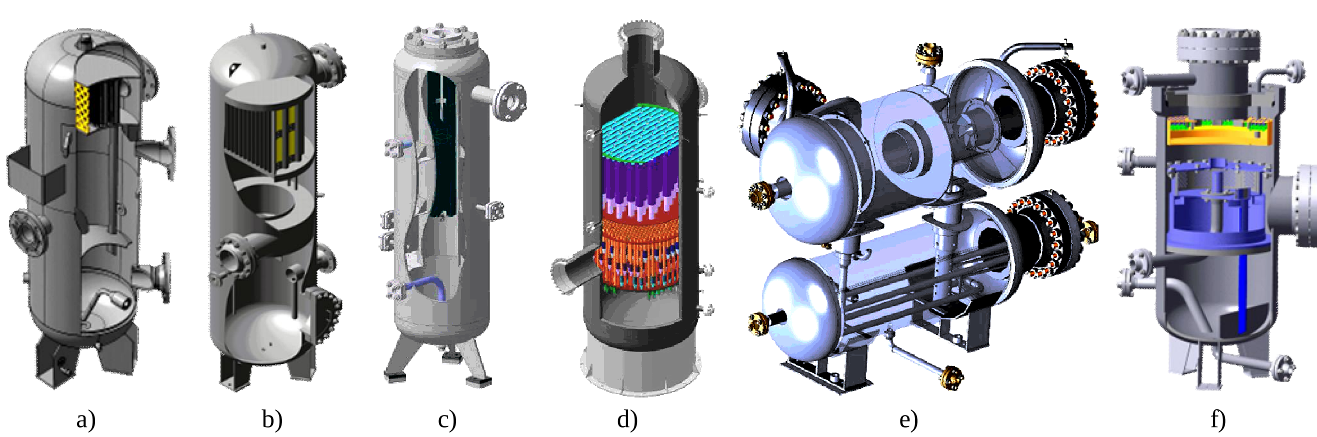


Fig. 1. 3D model of highly effective gas separators: louvre separator of the inertial type (a); louvre separator of the filter inertial type (b); vortex separator with the cartridge filter (c); separator for natural gas thin cleaning with centrifugal elements and the section of mist elimination (d); block inertial gas-dynamic separator with vortex and louvre blocks (e) and a mass transfer counter-vortex separation device for natural gas dehydration

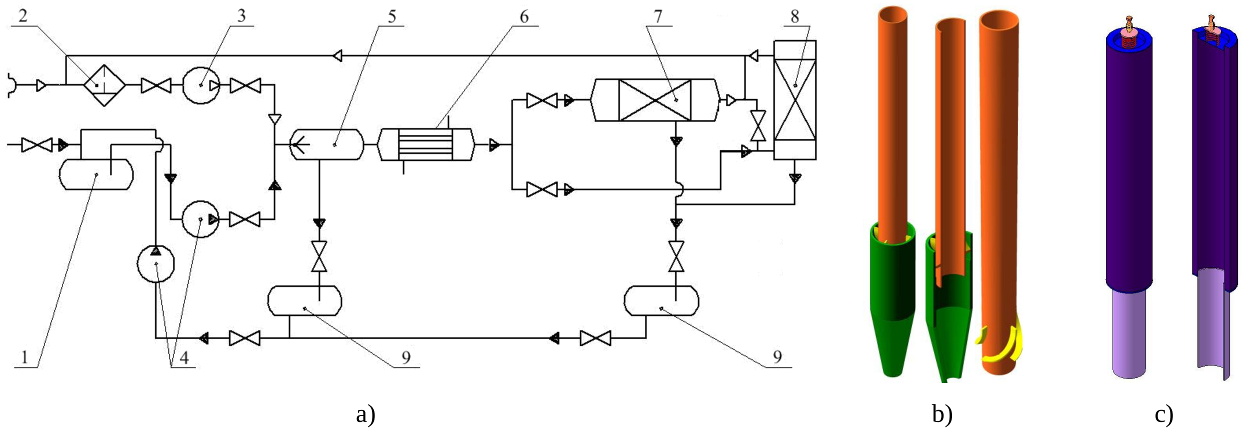


Fig. 2. Experimental plant for hydrodynamics investigation during separation of two-phase flows: experimental stand (a); drop catcher (inertial cyclone element) (b) and mist eliminator (filter-coalescer) (c). For experimental stand (a): vessel (1, 9); filter-drier (2); blower (3); pump (4); mixing chamber (5); heat exchanger (6); 1st stage of separation, drop catcher (7) and 2nd stage of separation, mist eliminator (8)

Virtual 3D computer modeling of two-phase gas flow with a highly dispersed dropping fluid which moves along the created 3D solid models of separation and mass transfer elements has been created to visualize these flows by computer graphic [2]. The distribution character of local velocities of natural gas which moves along separation zones and obtained as a result of computer modeling is in good agreement with the experimental results of hydrodynamic processes on the model samples. Visualization of three-dimensional flow simulation results in determining the values of flow hydrodynamic parameters (field of velocities and flow kinetic energy, field of pressures and corresponding resistance areas) in the separation zones, the geometry of reduced pressure and vortex formation zones, critical velocities and most reliable zones of spray entrainment. As a result, it is possible to accurately determine the location of the expedient arrangement of the filter elements, to optimize the geometry and dimensions of the inertial and centrifugal separation elements.

3. Results and Discussion

After the analysis of existing constructions we determined the most optimal device in terms of separation efficiency, operational performance and cost of manufacturing. It is a cyclone element of "rosette" type with four blades which change the slope angle. This design allows to achieve a high efficiency at a relatively low hydraulic resistance (Fig. 3). The use of blades with exchangeable slope angle excludes the possibility of the fluid film "creep".

For the second stage of separation it is necessary to use the devices providing the necessary degree of purification. Separation filter elements of different designs may be such devices. Filter-coalescers are the best at this stage to obtain the product of high purity [7, 8]. Fiber diameter is 25 μm, coagulating layer thickness is 16 mm, and filter layer thickness is 5 mm. The principle of operation is following: finely dispersed fluid phase remained after the first stage of gas cleaning is directed to the filter. Then, drops are combined in the coagulating layer to form larger drops which are able to be trapped by the next layer of the filter. Thus we get clean and dry gas at the outlet of the device.

Simulation studies of hydrodynamic processes and determination of the separation efficiency are based on the entrapping of particles (fluid drops) in the filter layer *via* mechanism of Brownian, diffusion and inertial coagulation. The calculated guaranteed efficiency of the second stage separation (block of cartridge filter-coalescer) of investigated gas separator is represented in Figs. 4 and 5. The coefficient of particles overshoot $K \leq 3.8$ %.

Hydraulic resistance of two-phase flow is determined as the sum of resistance components provided by gas flow moving and presence of suspended particles (drops) in it. On the other hand, it is composed by different mechanisms of separation (inertial and filtering ones).

The experimental study of hydraulic resistance was carried out using scale models of drop catcher and mist eliminator (Figs. 6a and 6b, respectively).

Hydraulic resistance of both devices is calculated in accordance with the formula:

$$\Delta P = \Delta P_g + \Delta P_f = x_g \frac{w^2 \cdot r_g}{2} + x_f \frac{w^2 \cdot r_f}{2} \cdot \frac{F}{G}, \text{ Pa}$$

where ΔP_g and ΔP_f – hydraulic resistance of gas and gas-fluid flows, respectively; x_g and x_f – coefficients of hydraulic resistance while movement of gas and gas-fluid flows, respectively; r_f – water density, kg/m^3; F/G – unit rate of trapped flow.

At first it is necessary to measure the pressure difference using only the gas flow and to determine the coefficient of hydraulic pressure x_g. Then – using the gas-fluid flow and knowing x_g we determine x_f.

The experimental results show that the resistance of separation elements while movement of gas-fluid flow is higher than that of one-phase gas flow (Fig. 6). Moreover, it increases with the increase in velocity of both flows.

The experimental results of gas cleaning efficiency h depending on hydraulic resistance are represented in Fig. 7.

One can see that the separation efficiency is lower for drop catcher compared with that of mist eliminator. It increases with the increase in *L/G* ratio but entrapping efficiency for high-dispersive particles (drops) insignificantly depends on water content of gas flow.

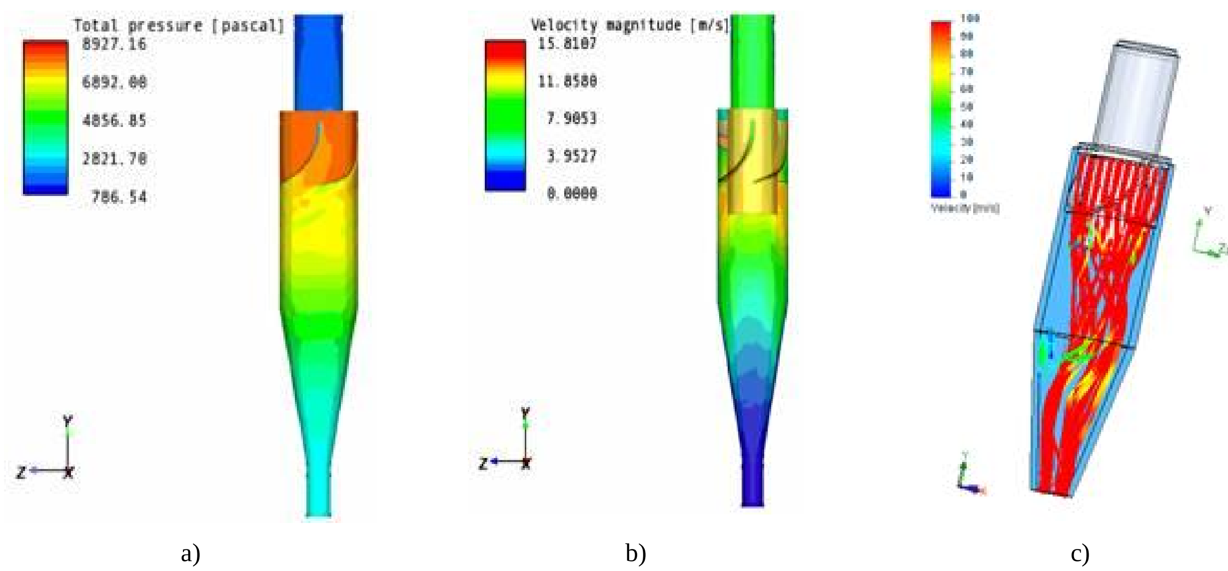


Fig. 3. Visualization of computer experiments: pressure difference on a cyclone wall (a); local velocities of gas flow along cyclone longitudinal section (b) and visualization of flow structure (particles motion path) (c)

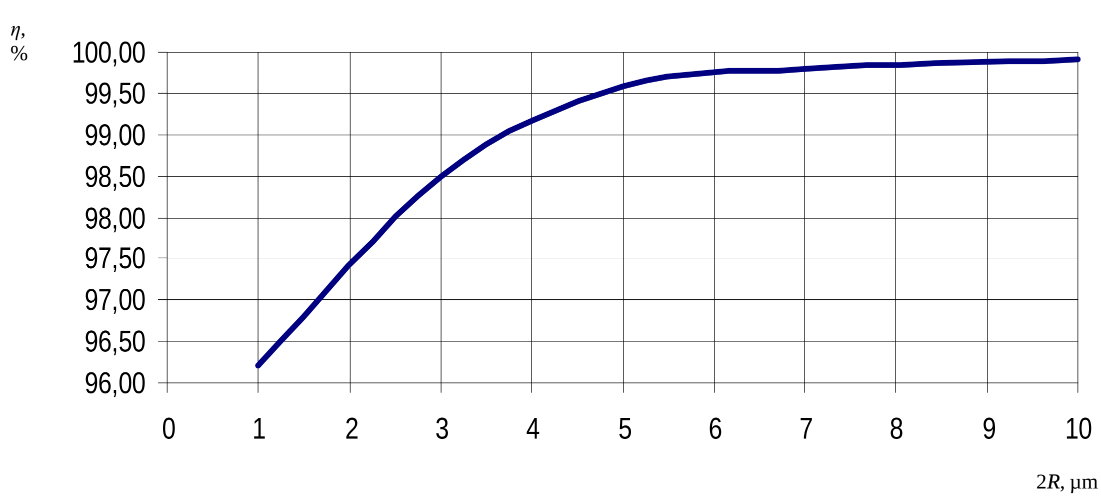


Fig. 4. Entrapping efficiency at the 2nd stage of separation (filter-coalescer)

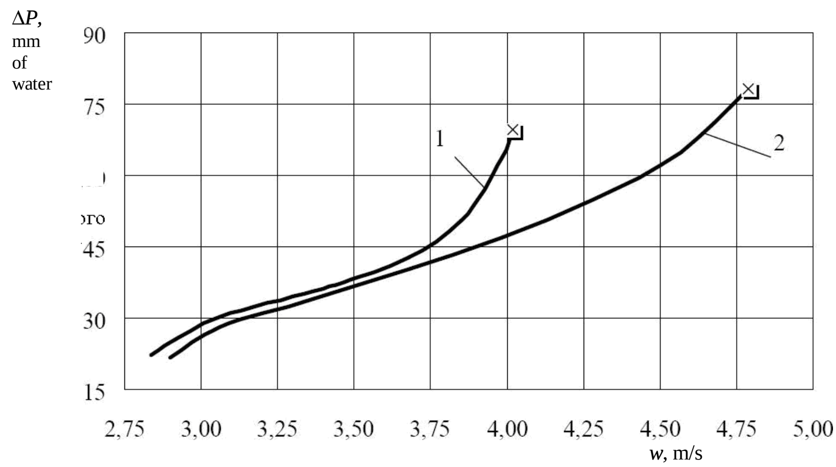
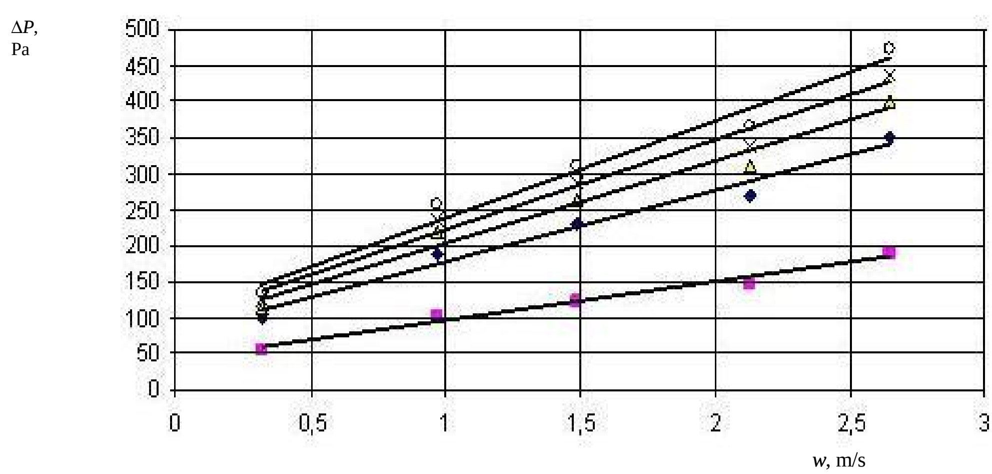
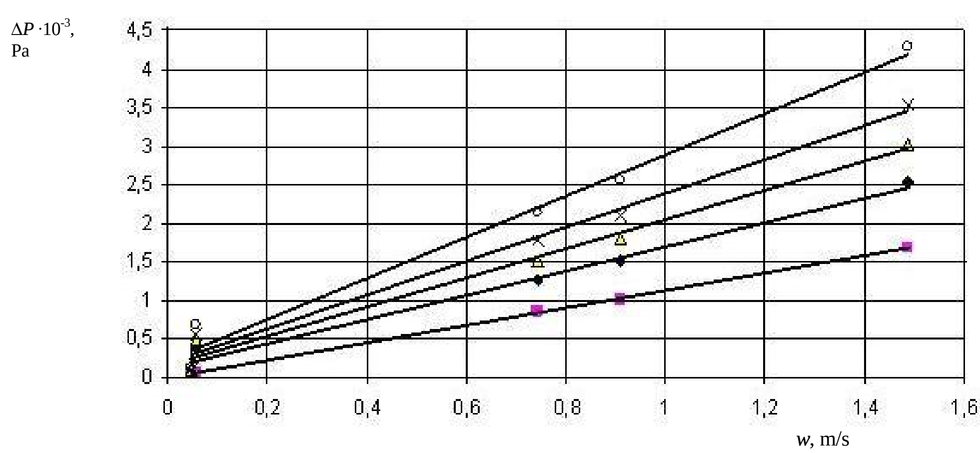


Fig. 5. Dependence of hydraulic resistance on gas flow velocity: gravity-inertial separator (1) and inertial filtering drop catcher (2). Critical point of phase inversion (X) corresponds to the flood mode

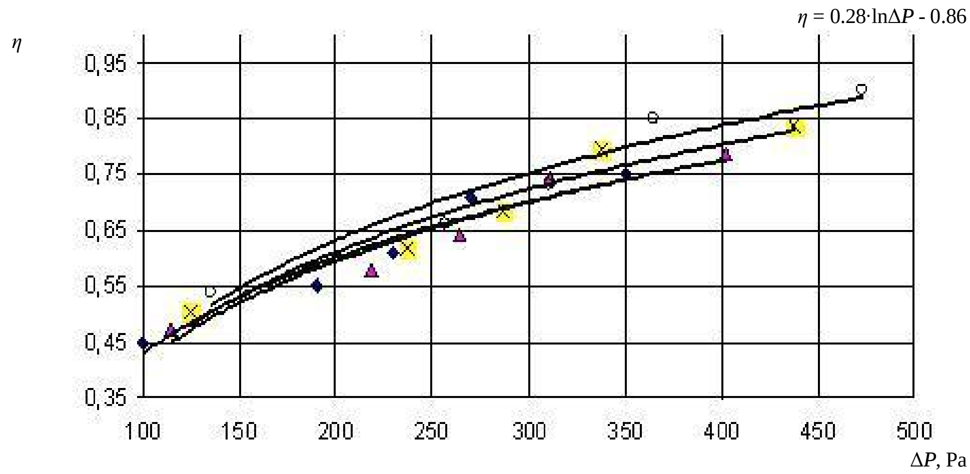


a)

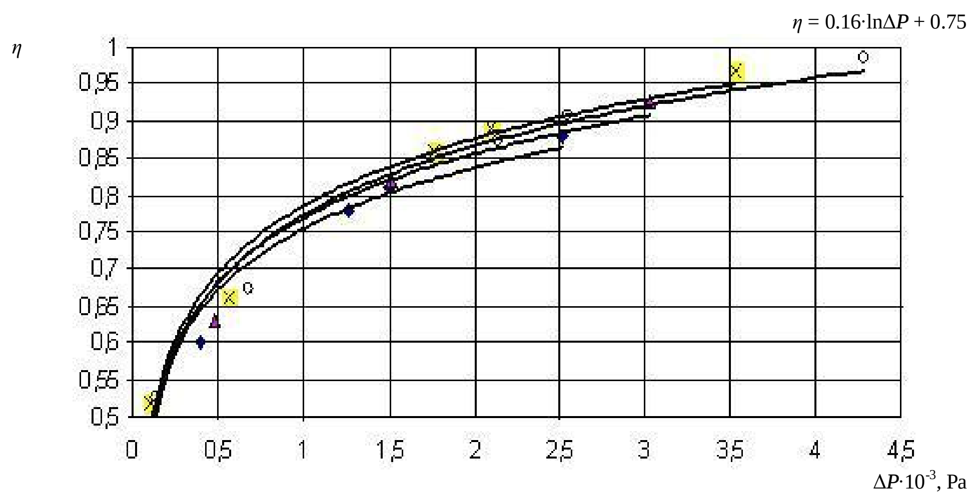


b)

Fig. 6. Dependence of hydraulic resistance of drop catcher (a) and mist eliminator (b) on unit rate of trapped fluid at gas and aerosol movement: ■ – F/G = 0; ◆ – F/G = 0.05; △ – F/G = 0.10; × – F/G = 0.15; ○ – F/G = 0.20



a)



b)

Fig. 7. Dependence of entrapping efficiency on hydraulic resistance of drop catcher (a) and mist eliminator (b): ■ – $F/G = 0$; ◆ – $F/G = 0.05$; △ – $F/G = 0.10$; × – $F/G = 0.15$; ○ – $F/G = 0.20$

It was observed during the experiments that within the range of gas-fluid operating flow velocities of 0.15–0.30 m/s (upper limit of the low-rate operation mode of fiber filters) the hydraulic resistance of cartridge element of filter-coalescer is low ($\Delta P \leq 24$ Pa).

The comparative characteristics of traditional and modern gas separators operated under the same conditions confirms the advisability of using original separation and contact elements. The dew point of gas decreases by 4–5 K and the hydrodynamic mode of two-phase flow becomes more intensive without critical behaviour, when the flood of filtering elements and drops reentrainment from the separated surfaces take place [9].

The general scheme of separation in the two-stage gas separator for natural gas fine cleaning can be represented as following: the flow with a definite distribution of particles (solid particles and fluid drops) is fed to the separator inlet by the size of $n_0(R)$ (Fig. 8).

At the first stage of separation, which is characterized by a minimum radius of drops R_m, all particles with $R > R_m$ are trapped (area on the right side of the dotted line limited by a distribution curve $0R$). At the first stage of separation, in addition to the drops with $R > R_m$, the part of particles with $0 < R < R_m$ (area on the left side of the dotted line limited by the distribution curves $0R$ and $0R_m$) is also trapped. In the layer of filter element, by which cartridge filters of the second stage are equipped with, the additional part (area is limited by the distribution curve $0R_{m1}$) is cut off from the drops distribution. This additional part is a high-dispersive component of the mixture. Moreover, while using vertical cartridges a stable removal of trapped fluid from the filter material is achieved. Fluid is removed as a film from the filter material as it is saturated, that prevents the possibility of the device flood mode and reentrainment. A small part of drops distribution with $0 < R < R_{m1}$ remains at the separator outlet. The introduction of drop minimum radius R_{m1}, which is determined by the filter element type, is conventional at this moment.

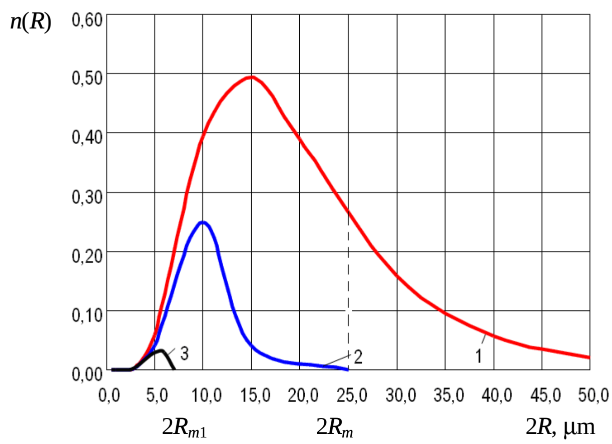


Fig. 8. The distribution of solid particles and fluid drops by size in the natural gas flow which are trapped by the first and second separation stages of device: distribution of the particles in the flow at the device inlet (first stage – battery block of cyclone unit) (1); distribution of the particles in the flow at the inlet to the second stage (block of cartridge filter-coalescer) (2) and residual distribution of the particles in the flow at the device outlet

4. Conclusions

Under stationary mode, at the absence of reentrainment and fluid volley effluent at the inlet the efficiency of investigated inertial-filtering separators and gas separator on the whole (h = 90–97 %) proportionally depends on their hydraulic resistance (ΔP = 3000–5000 Pa).

During experiments and computer simulation we determined general defects intrinsical to the investigated devices. The direct contact of gas flow and drops or film of the trapped fluid, intensive vortex formation and wave making together with improvement of separation conditions and removal of trapped fluid result in the destruction of fluid film structure and origin of spray entrainment the intensity of which is determined by a gas flow velocity.

The sufficiently high efficiency of gas cleaning from the dropping fluid (h = 80–97 %) is already achieved at flow velocity $w \geq 1.0$ m/s. The increase in flow velocity above 4.0 m/s sharply increases the hydraulic resistance and decreases the total efficiency of separation due to the origin of spray reentrainment. At the same time the structure of the flowing fluid film is destroyed in a drop catcher (inertial cyclone element) due to the high-intensive hydrodynamic mode. The flood of filtering layer (point of phases inversion) takes place in the mist eliminator (filter-coalescer).

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МОДЕЛЮВАННЯ ГІДРОДИНАМІКИ ІНЕРЦІЙНИХ ТА ФІЛЬТРУВАЛЬНИХ ЕЛЕМЕНТІВ ГАЗОСЕПАРАТОРА ТОНКОГО ОЧИЩЕННЯ ПРИРОДНОГО ГАЗУ

Анотація. *Розглянуто тенденції розвитку сучасного газосепараційного обладнання. На основі комп‘ютерного моделювання розраховано оптимальні розміри апарату. Приведено обгрунтування вибору комп‘ютерного і математичного експерименту як метода досліджень. Показані результати експеримента стосовно двоконтурного пиловловлювача.*

Ключові слова: *газосепарація, моделювання, інерційний та фільтрувальний елемент, розділення, газорідинна система.*