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Dust Collector for Paraffin Dehydrogenation Units with a Fluidized Catalyst Bed

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Abstract—The problem of trapping solid particles in a production line with dehydrogenation of C_4–C_5 *iso*-paraffins to *iso*-olefins in a fluidized catalyst bed was considered. Dust collection of fine catalyst particles for paraffin dehydrogenation units using a standard TsN-15 cyclone and a new dust collector (NDC) with arc-shaped elements was studied. The results of numerical simulation of TsN-15 and NDC were presented. Comparative studies showed NDC to be more efficient than TsN-15 for trapping fine solid particles with sizes of less than 20 μm. The pressure and flow velocity profiles for NDC were shown to change as a regular tendency, without any critical deviations. The gas flow velocity through the arc-shaped NDC elements was shown to be stable in contrast to TsN-15, which creates high flow velocities at the cyclone periphery to increase the probability of dust breakthrough into the flow.

Keywords: catalyst dust, cyclone, dust trap, arc-shaped element, efficiency

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INTRODUCTION

In petrochemical industry, dehydrogenation of C_4–C_5 isoparaffins into *iso*-olefins in a fluidized catalyst bed has become a widespread process. It uses an aluminum–chromium catalyst (such as IM-2201 or KDI), which is a fine powder with a particle size varying from 10 to 125 μm. The average particle size is 50–60 μm [1, 2]. The fractional composition of the catalyst is important as it can change because of crushing and attrition of particles when they collide with one another and with the reactor walls. This change in the fractional composition of the catalyst toward dust formation due to the destruction of particles should be taken into account in calculations of apparatuses as it can be critical [3–5].

The units for dehydrogenation of paraffins in a fluidized catalyst bed have a disadvantage: low efficiency of existing dust collection systems, because of which they fail to satisfy the growing requirements to reduce the catalyst consumption and improve the process ecology [3]. Air pollution with fine dust (of less than 20 μm) mostly of industrial origin has become an important problem.

Various devices used in industry for gas purification include vortex, gravitational, contact, and inertial dust collectors, including cyclones. Cyclone separators for gas purification from solid particles are often used in industrial processes for two-phase flow separation (for separating the high density phase from the lower density carrier phase using a rotating flow). Modern industrial cyclone designs allow operation at elevated temperatures and moderate to high loads of solid particles, meeting the requirements to separation efficiency with low investment and maintenance costs. This led to frequent use of cyclones at the preliminary stage of separation and purification compared to other industrial separators such as bag filters, electrostatic separators, etc. Examples of the industrial use of cyclone separators are gas purification from solid particles in high-temperature heat exchangers [1], for example, in cement industry; gasification and com-

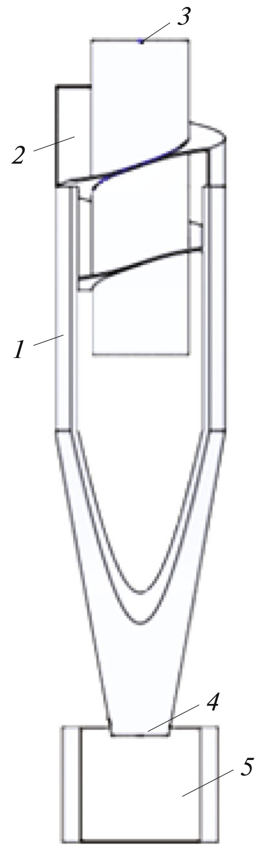

Fig. 1. Section view of the TsN-15 cyclone: (*1*) cyclone case, (*2*) inlet branch pipe for gas contaminated with the catalyst, (*3*) purified gas outlet; (*4*) outlet for catalyst particles trapped as a result of purification, and (*5*) bowl.

bustion of solid fuels [2, 3, 6]; coal pyrolysis [7]; and gas purification from solid particles in circulating fluidized beds (CFBs) [8].

To gain deeper insight into the physical processes and the factors affecting two important operating parameters of cyclones (pressure drop and separation efficiency), single-phase flows and flows of gas separated from solid particles have been widely studied in experimental cyclones using experimental methods (e.g., [2, 9–15]).

TsN-15 cyclones are widely used in dehydrogenation of paraffins (Fig. 1), including for low and medium degrees of gas purification; the design of these cyclones allows for the peculiarities of dust. However, they have disadvantages: relatively low efficiency for dust fractions of up to 5–10 μm. This is determined by some features of cyclone operation, in particular, turbulization of the flow of dusty medium, which prevents the separation of dust [7]. The large size of the apparatus necessitates high separation factor and high rates, leading to increased hydraulic resistance and high energy consumption.

To improve the efficiency of gas purification from small (5–10 μm) catalyst particles, research is under way to develop new dust collectors [8, 16–18]. For example, the results of a comparative study of TsN-15/TsN-15 and TsPKI/SKTsN cyclones for internal dust collector systems located in the dome of the reactor and regenerator were reported in [3]. It was shown that the new dust collector systems are more efficient than TsN-15 and can reduce the specific consumption of the catalyst, the amount of sludge, fouling of equipment, particle penetration, and the amount of entrained catalyst.

A rectangular separator with H- and U-shaped elements has been proposed [9]. It has increased (compared with TsN-11-400) efficiency with respect to fine particles (10–20 μm) at decreased hydraulic resistance. Therefore, it was interesting and useful (from the viewpoint of application for paraffin dehydrogenation) to study this separator. Thus, solving the problem of increasing the degree of purification of equipment from catalyst dust is a challenge.

The goal of this study was to develop a highly efficient dust collector that allows the removal of catalyst dust from the fluidized bed in the reactor. The assessment of the new dust collector (NDC) in comparison with the TsN-15 cyclone by means of modeling and calculations will allow us to evaluate and confirm the feasibility of upgrading the equipment of dehydrogenation units.

EXPERIMENTAL

New dust collector consisting of several lines of arc-shaped elements enclosed in a rectangular case was developed. To provide equal flows, the arc-shaped elements are located at an angle of 30° in the device. A simplified model of a dust collector with arc-shaped elements is shown in Fig. 2. The arc-shaped elements are attached to the case surface on one side and to a grate welded to bowl (*4*) on the other.

The principle of operation of the device with dust-collecting elements is as follows: a dusty gas flow enters the apparatus through inlet branch pipe *2*, after which it moves straightforwardly to arc-shaped elements *3*, reaching them, and then moves into the narrow regions between the separation elements. As the arc-shaped elements are in staggered arrangement, the dusty gas flow acquires a wave-like shape. The structural parameters have a special effect on the formation of the wave structure of the gas flow motion inside the device. In particular, to achieve the maximum value of centrifugal forces arising when the gas goes around the arc-shaped elements, the following condition should be satisfied: the separation elements should be located such as to from the central point of a circle of two combined arc-shaped elements it would be possible to draw a circle equal to two of its diameters and passing through the central points of the extreme straight

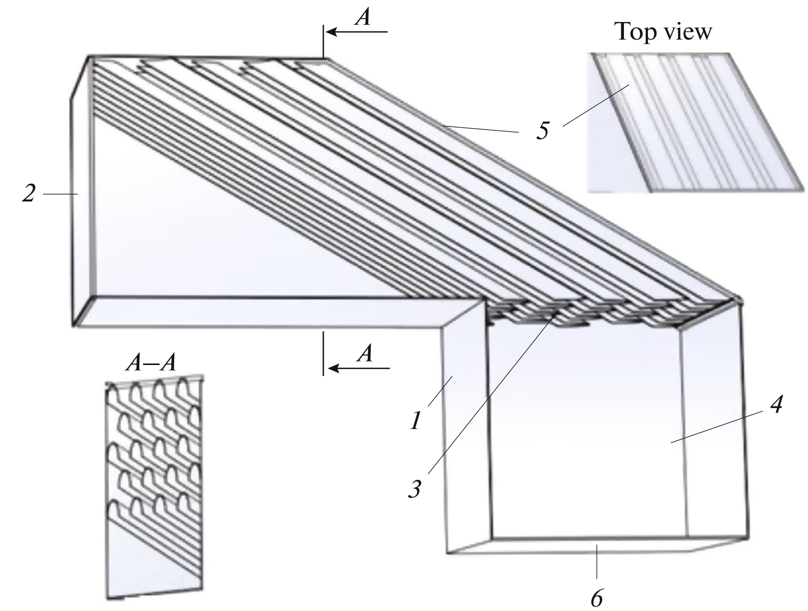

Fig. 2. New device with dust collecting elements: (*1*) case, (*2*) inlet branch pipe for contaminated gas, (*3*) dust collecting elements, (*4*) bowl, (*5*) outlet for purified gas, and (*6*) outlet for precipitated dust particles.

edges—the neighboring elements lying in the previous and subsequent rows.

Thus, the centrifugal forces that formed during the movement of the dusty flow between the arc-shaped elements knock out the particles from the flow and they fall on the surface of the element walls. Then the particles gradually settled along the height of the device and entered the bowl. After the gas moved through several lines of arc-shaped elements, it left the device through outlet pipe *5*. The precipitated particles in the bowl are poured out through outlet *6* for precipitated dusty particles.

To obtain comparative data for the TsN-15 cyclone and the proposed device with dust-trapping elements, numerical simulation was performed in the SolidWorks software package. For this, three-dimensional models of the devices were constructed. The TsN-15 cyclone was constructed according to known dimensions, and the proposed new device was designed by the size selection method. In the proposed device (Fig. 2), the arc-shaped elements have a constant geometrical shape. The radius and length of the arc-shaped elements are 6 and 176 mm, respectively.

The gas flow was steady-state; the concentration of solid particles was low, so their interaction with one another was neglected. Boundary conditions: the velocity was set at the inlet and varied from 5 to 25 m/s; the pressure was set at the outlet, 0.6 kgf/cm^2. The particles under study had a density of 1400 kg/m^3; the particle diameter was 5–80 μm. The number of points n at the inlet of the apparatus was 1000. The condition of reflection was set on the surfaces of the TsN-15 cyclone and the proposed device with arc-shaped elements; and the condition of sticking, at the bottom of the bowl.

The efficiency of dusty gas flow purification from fine particles was calculated by the following equation:

$$E = 1 - \frac{n_k}{n}, \quad (1)$$

where n_k is the number of particles in the gas that remained in it after its purification in a separator.

The pressure drop in TsN-15 and NDC was determined by the equation

$$\Delta p = p_{\text{inlet}} - p_{\text{outlet}}, \quad (2)$$

where p_{inlet} is the pressure at the inlet of the device, Pa; and p_{outlet} is the pressure at the outlet, which is equal to the atmospheric pressure, Pa.

RESULTS AND DISCUSSION

The results of comparative evaluation of the efficiencies E of the TsN-15 and NDC cyclone models are presented graphically in Figs. 3 and 4. For TsN-15, the efficiency is high, and its design allows the removal of particles of 15–20 μm or more, which confirms the literature data [3]. For the standard operating conditions (gas flow velocity, 17 m/s), particles of 15–80 μm are captured with $E = 100\%$. At a gas flow velocity decreased to 5 m/s, TsN-15 operates less well; particles of 20–30 μm are captured with an efficiency of 70–80%, and dust of 5–15 μm is not removed at all. Thus, complete purification of dusty flows from solid particles at gas flow velocities of 5, 17, and 25 m/s in a cyclone is achieved at parti-

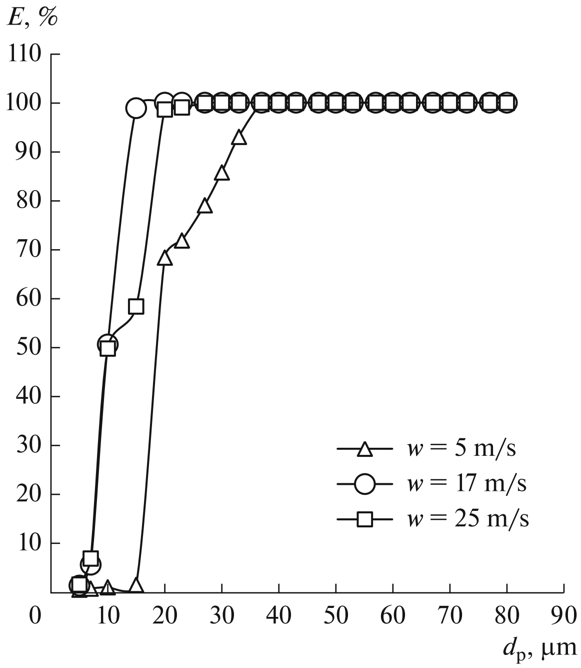

Fig. 3. Degree of gas purification in a single-stage cyclone versus size of dust particles at the inlet at gas flow velocities of 5, 17, and 25 m/s.

cle sizes of more than 40, 20, and 19 μm, respectively. The cyclone efficiency is on the average 50.2% (at a flow velocity of 5 m/s), 39.1% (17 m/s), and 65.9% (25 m/s) at particle sizes of less than 40, 20, and 19 μm, respectively (Fig. 3).

The results of numerical calculations of NDC showed that at gas flow velocities of 5–17 m/s and particle diameters of 30–80 μm, its efficiency is lower (E = 80–99%) than for TsN-15, but when the flow velocity increases to 25 m/s, its work improves. At the same time, for small particles (5–20 μm), the trapping efficiency of NDC is higher than that of TsN-15. For particles of up to 20 μm, the efficiency of NDC is 31.4, 57.2, and 58.2% at gas flow velocities of 5, 17, and 25 m/s, respectively (Fig. 4). The results correlate with the data presented in [10].

An analysis of the results showed that the pressure drop in NDC increases from 10.8 to 300 Pa when the inlet flow velocity increases from 1 to 17 m/s. The obtained dependence of the pressure drop in NDC on the inlet gas flow rate can be divided into three regions: the first region is limited by the range of inlet gas flow velocities from 1 to 5 m/s, the pressure loss being from 10.8 to 26.38 Pa; the second region is limited by the range of inlet gas flow velocities from 5 to 10 m/s, the pressure drop being from 26.38 to 103.87 Pa; and the third region is limited by the range of inlet gas flow velocities from 10 to 17 m/s, the pressure loss being from 103.87 to 300 Pa. On passing to a region with higher velocities, the pressure drop in NDC evidently increases. This is caused by a change in the flow structure during the gas passage between the lines of arc-shaped elements and by the appearance of additional vortices (Fig. 5).

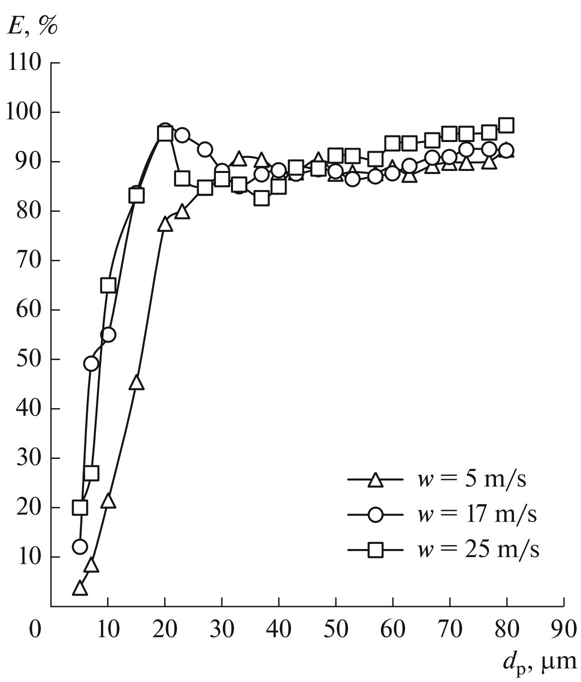

Fig. 4. Degree of gas purification in a single-stage cyclone (NDC) versus size of dust particles at the inlet at gas flow velocities of 5, 17, and 25 m/s.

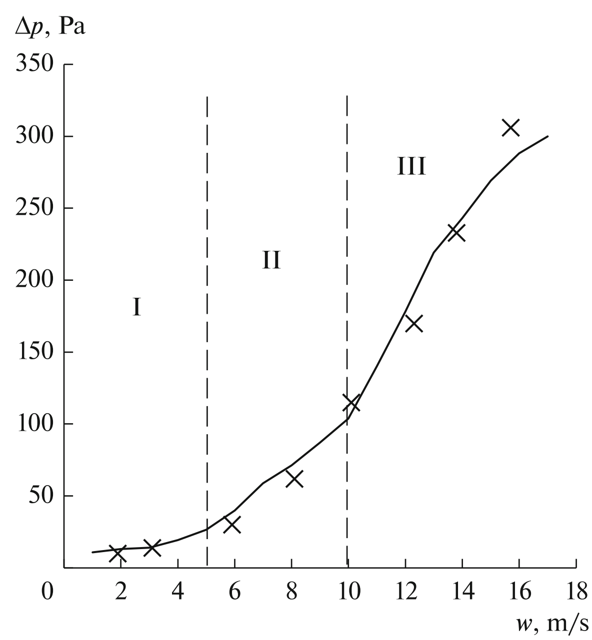

Fig. 5. Pressure loss in NDC versus inlet gas flow velocity. Solid line: numerical simulation; dots: experimental data.

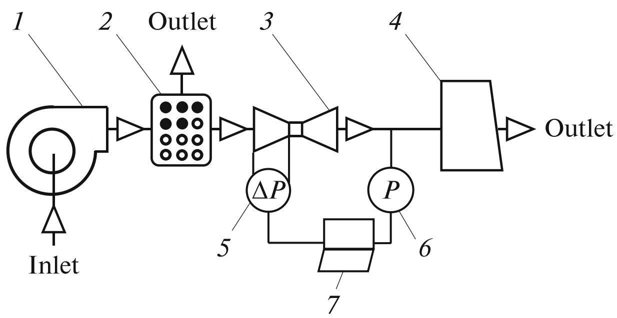

Fig. 6. Experimental unit for studying the resistance of a separator with inclined separation elements: (*1*) fan, (*2*) receiver, (*3*) Venturi tube, (*4*) separator with inclined separation elements, (*5*) and (*6*) differential pressure gages, and (*7*) computer.

Note that when the arc-shaped elements are blocked, the vacant space in the inner cavities decreases; as a result, the number of reverse currents decreases, as does the pressure drop in NDC [9]. In this case, the pressure loss in the cyclone separator is up to 1 kPa.

To check the adequacy of the numerical simulation, an experimental unit was created (Fig. 6). Its main elements are: fan *1*, receiver *2* with several lines of round holes on all sides, Venturi tube *3*, separator *4* with inclined separation elements, differential pressure gages *5* and *6*, and computer *7* for data recording. The gas flow was pumped by a fan, and then the gas passed through the receiver. During the experiment, the holes in the receiver were sequentially opened to reduce the gas flow flow velocity. After the receiver, the gas entered the Venturi tube with the first differential pressure gage *5* connected to it (which recorded the pressure difference between the wide and narrow parts of the tube); the data were transmitted in real time to the computer. Then the gas went along the air flow line to the separator with inclined separation elements. The second differential pressure gage *6* was installed in front of the separator, which recorded the excess pressure in the line and transmitted the data to the computer. The hydraulic resistance of the separator with inclined separation elements was calculated as the difference between the pressure indicated by the differential pressure gage *6* and the ambient pressure at the outlet of the separator. The pressure drop in the Venturi tube and the pressure at the inlet to the device were measured with a TESTO 510i differential pressure gage, whose measurement error was ±5.0% in the

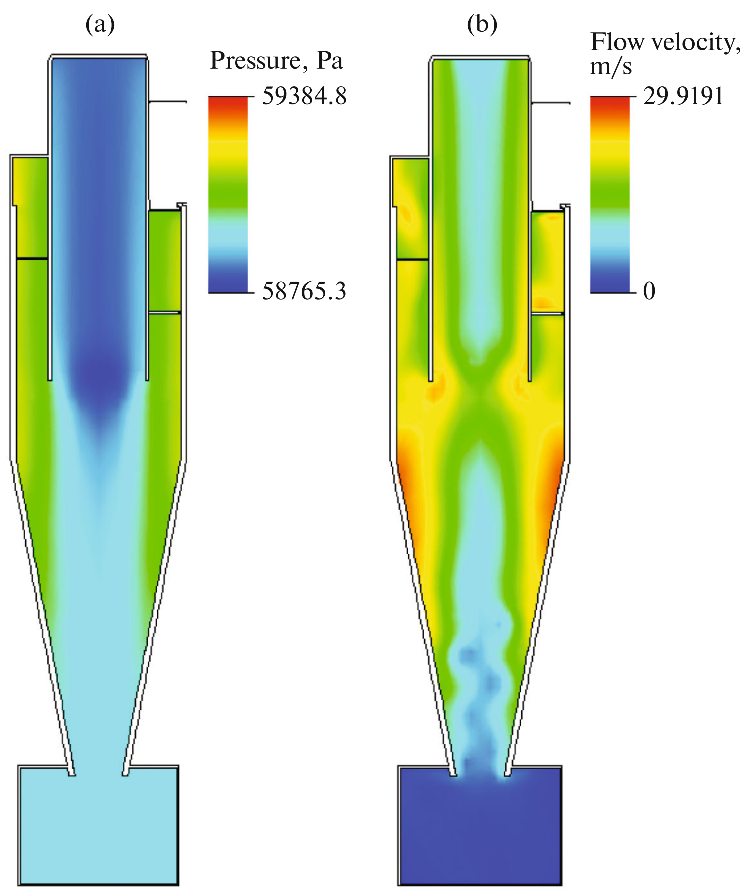

Fig. 7. Profiles for the (a) pressure and (b) flow velocity in cyclone TsN-15.

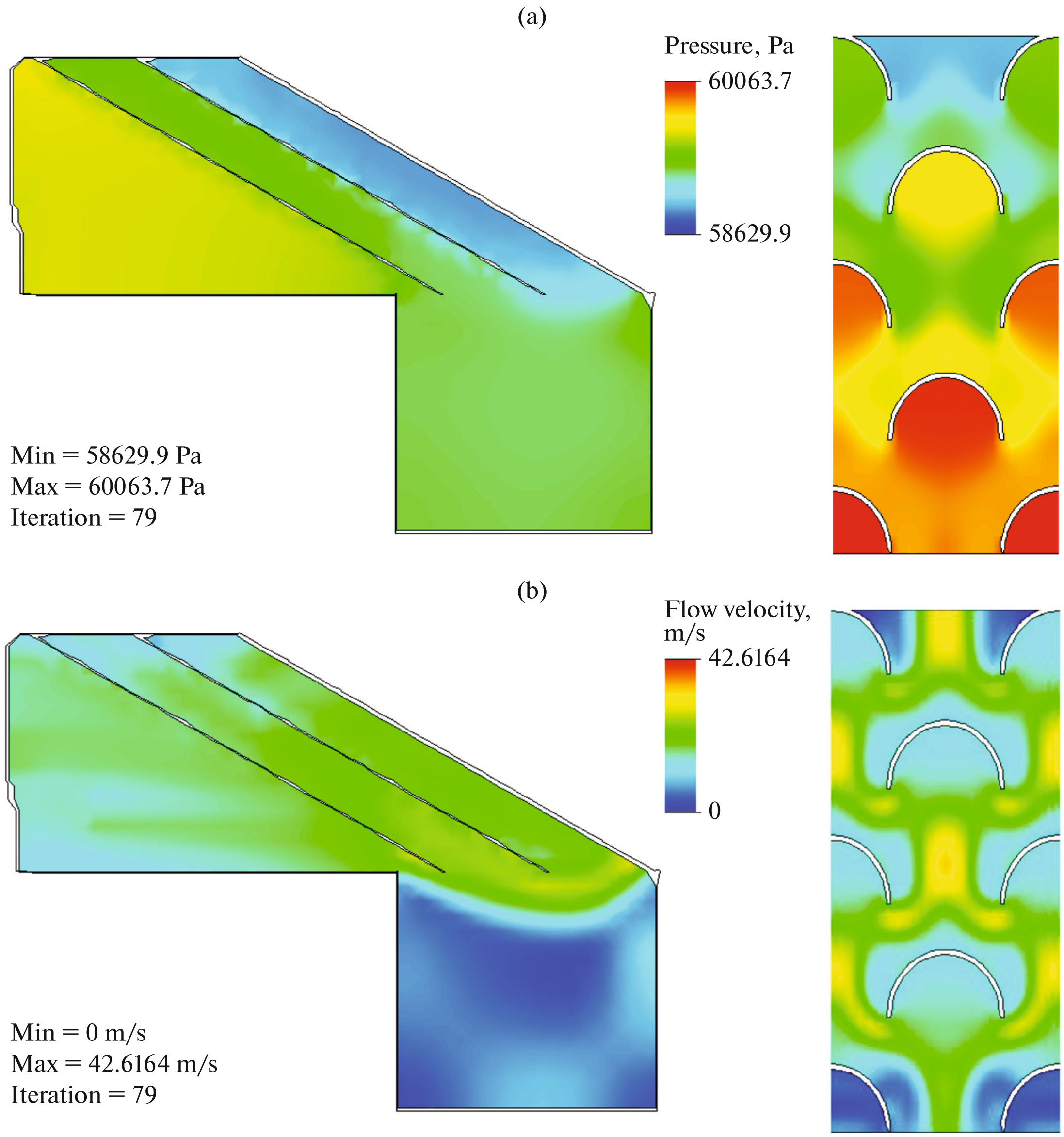

Fig. 8. Profiles for the (a) pressure (side view, left view) and (b) flow velocity (side view, left view) in NDC.

measurement range 0–100 Pa and ±3.5% in the measurement range 100–1000 Pa.

The *k*–ω SST turbulence model was used in the numerical simulation. The partial differential equations were also specified (Navier–Stokes equation):

$$\frac{\partial \vec{v}}{\partial t} = -(\vec{v} \cdot \nabla)\vec{v} + \nu \Delta \vec{v} - \frac{1}{\rho}\nabla p + \vec{f}, \quad (3)$$

where ∇ is the nabla operator; Δ is the Laplace vector operator; t is the time, s; p is the pressure, Pa; $\vec{v}$ is the velocity vector field; and $\vec{f}$ is the vector field of bulk forces.

The Navier–Stokes equation was complemented with the continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0. \quad (4)$$

The results of our experimental studies are in satisfactory agreement with the results of the numerical simulation. The deviation is no more than 10%, which is acceptable for engineering calculations.

Figures 7 and 8 show comparative data on the predicted flow velocity and pressure profiles. It can be seen that the pressure and flow velocity profiles for NDC change according to a certain tendency, and no critical deviations are observed.

Around the separation elements, the flow is ordered and close to the laminar mode in its structure as the distance between the separation elements is relatively small. The gas flow velocity in the NDC is stable, in contrast to TsN-15, where increased vortex velocities are created along the cyclone edges, leading to wearing and to a turbulent gas flow, which increases the probability of penetration of small particles.

Thus, our studies showed the importance of using NDCs for trapping particles in technological lines with dehydrogenation of C_4–C_5 isoparaffins to *iso*-olefins in a fluidized catalyst bed as the efficiency of trapping fine particles of less than 20 μm increases on the average by 21.2% compared with the efficiency of the TsN-15 cyclone. To increase the efficiency of trapping solid particles larger than 20 μm, it is possible to use an additional line of arc-shaped elements. It is advisable to use NDC at gas flow velocities of up to 10 m/s as the pressure drop in the device is not more than 103.87 Pa. At increased flow velocities, the structure of the gas flow changes, as a result of which the pressure drop in the device increases significantly.

CONCLUSIONS

A new dust collector (NDC) has been proposed for separating a wide fraction of particles; it can be used in industrial processes for removing the catalyst dust in paraffin dehydrogenation units.

In the TsN-15 cyclone, particles smaller than 20 μm are not trapped at low flow velocities and penetrate into the flow to be purified. The efficiency of NDC is higher on the average by 21.2% than that of TsN-15 in trapping particles of up to 20 μm at gas flow velocities of 5–25 m/s.

The pressure and flow velocity profiles for NDC change according to a certain tendency, without any critical deviations. The gas flow velocity through the arc-shaped elements of NDC is stable, in contrast to that in TsN-15, in which high flow velocities are created along the cyclone edges, which increase the probability of dust penetration into the flow to be purified.

The advantages of the new device are easy manufacturing and high degree of trapping fine particles.

The novelty of the new dust collector compared to other centrifugal separators lies in higher centrifugal forces. This is achieved as a result of the formation of numerous eddy points when the gas goes around the arc-shaped elements; the eddy radius is relatively small, and the higher centrifugal forces make it possible to separate particles smaller than 20 μm from the gas flows.

The device can be considered for use in a system with TsN-15, which could increase the efficiency of the industrial dehydrogenation of C_4–C_5 isoparaffins to *iso*-olefins in a fluidized catalyst bed.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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