Improving the efficiency of gas-liquid high-pressure cyclone separator

N.I. Mikheev\textsuperscript{1,2}, V.A. Fafurin\textsuperscript{3}, D.V. Kratirov\textsuperscript{2}, A.E. Goltsman\textsuperscript{1}, A.A. Paereliy\textsuperscript{1}, I.I. Saushin\textsuperscript{1}

\textsuperscript{1} Kazan Scientific Center of the Russian Academy of Sciences, Lobachevsky str. 2/31, Kazan, 420111, Russian Federation
\textsuperscript{2} Kazan National Research Technical University named after AN Tupolev - KAI, 10, K.Marx St., Kazan, 420111, Russian Federation
\textsuperscript{3} Federal State Unitary Enterprise “All-Russian Research Institute of Flow Metering”, 7A, Vtoraya Azinskaya str., Kazan, 420088, Russian Federation

E-mail: an116ya@mail.ru

Abstract. The research results focused on improving the efficiency of gas-liquid cyclone separator with high operating pressure value of 2.5 MPa and a high flow density in the separation chamber are presented. With increasing of the gas dynamic pressure value increases the probability of entrainment processes and ascending film flow on the chamber walls which leads to a decrease of the separation efficiency. The gas-liquid separator construction provided the gas dynamic pressure reduce in the areas with high concentration of the liquid phase and excluded the separated liquid removal to the output collector is performed. This collector formed by conical confuser and round tube with external finning is located in the center of the separator’s cylindrical chamber. A ribbed tubular flow conditioner is placed before collector’s inlet face. The detailed structure of the flow in the separator by using a computational fluid dynamics based on RANS equations solving with the anisotropic RSM turbulence model is obtained. CFD simulation results are used to evaluate the main separator characteristics and the probability of entrainment processes and ascending film flow.

1. Introduction
Separators are an important element of gas treatment systems and have wide application in various sectors of industry. The range of application and technical requirements contributed to the creation of a greater variety of designs, which differ not only in their efficiency, but also in the fundamental laws of physics used, such as inertia, gravity, and centrifugal acceleration.

The operating principle of the cyclone separators is the settling of particles by centrifugal forces. The high gas velocity inside the chamber of the cyclone separators provides a high value of the centrifugal force module, contributing to settling of particles $>5\mu m$ \cite{1} and as a result the centrifugal separators efficiency reaches 98-99.5\% \cite{2}. However, the efficiency of cyclone separators deteriorates significantly with a decrease in its overall dimensions \cite{3}. Nevertheless, the high efficiency of the cyclone separators with relatively low hydraulic resistance contributed to the choice of this class in most industrial technical systems.
When designing gas-liquid separator, in addition to predicting the probability of particle settling under the action of centrifugal forces, it is necessary to take into account the possible negative influence of two phenomena [4], the probability of which increases with increasing flux density.

The first phenomenon is called "layer losses" [5]. Under the action of centripetal acceleration, liquid droplets settle on the surface of the walls of the separator chamber where they form a liquid film falling by gravity to the liquid phase collecting area. With a dynamic pressure of the upflow of gas washing the collected liquid of more than 15-30 Pa, the energy of the flow will be sufficient to capture the liquid and create the ascending film flows on the vertical walls of the separator chamber, these film flows can eventually reach the output collector of the treated gas phase.

The second phenomenon is liquid-reentrainment (entrainment of droplets by the flow of gas from the surface of a separated liquid phase) [6], which arises when the dynamic gas head is above 140-1000 Pa [7]. According to [8], the entrainment becomes possible if the drag force from the high shear flow of gas acting on the wave crest exceeds the retaining force of the surface tension.

The negative influence of these processes on the separation efficiency increases with the increase in the dynamic pressure of the flow inside the separator chamber, which limits the possibility of using most cyclone separators intended for operation under near-atmospheric pressure, high pressure and flux density conditions. The maximum value of the dynamic head of upflows inside the separator chamber is rather difficult to estimate analytically or experimentally. Numerical modeling of the separator operation process allows not only to perform such estimation, but also to optimize the design of the separator to prevent the conditions for the emergence of ascending film flow and liquid-reentrainment.

The results of a study aimed at increasing the efficiency of a gas-liquid cyclone separator designed for high-pressure operation and high density of flow in the separation chamber are presented. The detailed structure of the flow in the separator on the basis of the numerical solution of the Reynolds-averaged Navier-Stokes equations (RANS) with the closure of the anisotropic Reynolds stress (RSM) turbulence model is obtained. The results of numerical simulation were used to predict the process of dispersed particle settling, the conditions for the occurrence of ascending film flow, and the phenomenon of liquid-reentrainment from the surface of a liquid film. Based on the results of the study, a constructive scheme of the separator for treatment the flow with a high density, which ensures a reduction in the dynamic pressure of the gas in zones of increased concentration of the liquid phase and excludes the entrainment of the already separated liquid into the output collector, is proposed.

2. Working principle of cyclone separator

A scheme of a gas-liquid cyclone separator designed for operation under high pressure and high flux density conditions is shown (figure 1). The inlet pipe 4 for the gas-liquid mixture is located in the top head 2 of the separator. The impeller 8 is located at the inlet pipe and is designed to form the rotational (cyclone) motion of the gas flow inside the separator. Meanwhile, the gas and particles are thrown to the wall. The impeller is formed by four vertical separation profiles with a curvature of 45° located circumferentially at an equal distance from the axis and the axial disk, bounded from above and from below by disks, figure 1 section A-A. The collector 7 formed by a conical confuser and a round pipe is located in the center of the cylindrical chamber 1 of the separator. There are 4 vertical anti-swirl blades on the outer surface of the conical confuser and the collector pipe. Before the input section of the conical confuser of the collector, a fin-tube flow conditioner is placed. Gas removal is carried out through the separated gas outlet pipe 5 in the bottom space 3 of the separator. This collector design due to the forced reduction of the tangential component of the flow velocity, and as a consequence of its dynamic head, suppresses the processes of the occurrence of ascending film flow and the phenomenon of liquid-reentrainment in the region of the increased concentration of the liquid phase. Separated as a result of the action of the centrifugal force, the liquid phase under the action of gravity collects in the region of the bottom space 3 and is discharged through the separated liquid outlet pipe 6.
3. Numerical simulation

Software FLUENT is used to analyze the flow field of cyclone separator, according to the method of CFD. The considered cyclone separator belongs to the class of treatment plants of the last stage with a small initial concentration of dispersed particles, therefore, in the numerical simulation, it was assumed that the dispersed phase does not influence the flow pattern of the carrier phase, and in predicting the trajectories of dispersed particles their collision, coagulation and crushing are disregarded [9]. The RSM model has been adopted. In the simulation, the control equation chose QUICK [4, 10, 11], the algorithm is set to SIMPLE [4, 10, 11], PRESTO is the pressure interpolation format [4, 10], and the second-order upwind scheme also been selected. The inlet boundary condition in inlet pipe 4, figure 1, is total pressure 2503 kPa, with density 30.2 kg/m$^3$, dynamic viscosity 1.79·10$^{-5}$ m$^2$/c; in separated gas outlet pipe 5 is static pressure 2500 kPa.

The standard wall function is chosen for the walls. In order to obtain the tracks of particles with different sizes and analyze the fractional efficiency of cyclone separator, the discrete phase model (DPM) is used to simulate. The Lagrangian DPM in ANSYS Fluent follows the Euler-Lagrange approach. The fluid phase is treated as a continuum by solving the Navier-Stokes equations, while the dispersed phase is solved by tracking of particles with a concentration of less than 10%. When a particle hits the wall, the particle is considered to be separated.

4. Results and discussion

Evaluation of the efficiency of cyclone separator based on the application of the DPM model was carried out on the analogy of [11] by bringing in the dispersed particles of different diameters into the separator and counting the number of deposited particles. The particle trajectories with a diameter of the order of 1 μm due to the small mass almost completely coincide with the flow lines of the carrier medium, so the percentage of their settling is rather small (50-60%). Further increasing the particle diameters to 20 μm increases the percentage of deposited particles to 97%. Complete settling was obtained for particles with a diameter of 20 μm or more. The obtained evaluation of the separation efficiency of particles of different diameters at high flux density corresponds to the efficiency of the separators intended for operation under atmospheric pressure conditions.

An estimation of the occurrence probability of ascending film flow formed by liquid dispersed particles deposited on the wall is performed on the basis of the dynamic pressure field obtained from the results of numerical simulation of the gaseous medium, figures 3-4. As seen, the dynamic head of...
the near-wall gas flow in the direction of the flowing liquid is very high and reaches 300 Pa. It is caused by downflow with a large tangential velocity. At such pressure the appearance of liquid-reentrainment from the surface of a liquid film is unlikely. However, the design of the separator very effectively extinguishes the velocity head when the flow is turned, and in the region of the upflows we see a completely different picture, figure 4. At a distance of about 150 mm from the bottom space, where an increased liquid phase concentration on solid walls is expected, calculations show a complete absence of the wall upflows. On the sections of the finned conical generatrix of the collector, washed by upflows, the dynamic head near the wall did not exceed 30 Pa. With such pressure value, there are no conditions for the emergence of ascending film flows from the surface of the bottom space.

5. Conclusion
The proposed design of a gas-liquid high-pressure cyclone separator, namely the device and arrangement of a collector for discharging treated gas, provides a reduction in the dynamic head of gas in the zones of an increased concentration of the liquid phase to a value of 100-200 Pa, while the dynamic head of the wall upflows with a value of not more than 30 Pa is fixed at a significant distance from the zone of collection and removal of the liquid phase. By an estimate based on the results of numerical simulation, it is shown that there are no conditions for the occurrence of ascending film flow and the phenomenon of liquid-reentrainment. Using the DPM model, it was possible to predict the separation efficiency of particles of different diameters, which corresponds to separators intended for operation in conditions close to atmospheric pressure. The proposed structural design of the separator provides a reduction in the dynamic head of gas in zones of increased concentration of the liquid phase and eliminates the entrainment of already separated liquid into the output collector.

Figure 2. The tracks of different size particles and the separation efficiency
Figure 3. Contours of dynamic pressure

Figure 4. Contours of dynamic pressure of upflows in the area of the bottom space

References
[1] Sun GG, Shi MX 2008 Modern Chemical Industry 28 64-69
[2] Kozlovsky EA 1984-1991 Moutain encyclopaedia. Soviet encyclopaedia (in Russian)
[3] Wu K, Genfan L, Yuchen M 2016 Powder Technol. 295 1–6
[4] Zhou, Hui Y 2013 Experimental and simulation studies on performance of a compact gas/liquid separation system
[5] Hoffmann AC, Stein LE 2008 Gas Cyclones and Swirl Tubes: Principles, Design and Operation: Springer.
[6] Zhiquan Z, Chen Q 2015 AASRI International Conference on Industrial Electronics and Applications, 491-494
[7] Kasatkin AG 1973 Basic processes and apparatures of chemical technology (in Russian)
[8] Ishii M, Grolmes MA 1975 AIChE Journal 21(2) 308-318
[9] Derksen JJ 2003 AIChE Journal 49 1359–1371
[10] Kaya F, Karagoz I 2008 Current Science 94 1273-1278
    Chen S, Liu P, Gong J 2017 Powder Technology 305 56-62