Reduction of Granular Material Losses in a Vortex Chamber Supercharger Drainage Channel

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Abstract. Increasing the reliability and durability of superchargers in pneumatic and hydraulic transport is possible due to vortex chamber jet superchargers. Their efficiency significantly exceeds pumping bulk mediums in pneumatic transport using direct-flow jet ejectors. However, the pumped medium losses in the vortex chamber supercharger drainage channel do not allow it to be widely used in such systems. Based on experimental and numerical studies, the influence of the density of the granular material on the losses in the drainage channel has been determined. Mathematical modeling was done by solving the Reynolds-averaged Navier-Stokes (RANS) equations with the Shear Stress Transport (SST) turbulence model. Rational densities of the medium can be varied by changing the vortex chamber height or swirling the inlet flow using a swirler. The design changes are explained by the kinematic features of the solid particle motion. If the vortex chamber height is small, then the particle does not have time to start rotating near the chamber axis and enters the supercharger drainage channel. The absence of the drainage channel in the design will lead to the outlet pressure decrease. As a result of the research, the granular material losses in the supercharger drainage channel have been reduced by 50%, with a twofold increase in the swirl number.

Keywords: Vortex chamber supercharger · Experiment · Numerical simulation · Drainage channel · Granular material losses · Energy efficiency · Process innovation

1 Introduction

Bulk cargoes pumping in hydraulic and pneumatic transport is accompanied by high wear of the blowers and pumps with the low reliability and durability of hydropneumatic transport systems [1, 2]. Ways to increase the durability of such systems are practically exhausted due to the limited choice of wear-resistant materials [3] and improvements of

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the pumps vane systems [4]. Increasing the reliability and durability of systems must be done with a simultaneous solution to the problem of growing energy-saving indicators and reliability [5].

The solution to the problems of the blower's reliability can be the use of jet superchargers [6]. Still, low-efficiency indicators prevent the widespread use of direct-flow water and two-phase ejectors. Using centrifugal force has made it possible to create more efficient devices for pumping granular materials - vortex chamber supercharger [1, 7]. Its efficiency when it pumps a bulk medium with air is more than twice as high as the efficiency of classical jet pumps. However, the working process of such a blower is implemented with the release of a part of the pumped medium through the drainage channel, which creates significant inconveniences in its use. Thus, improving the design of a vortex-chamber supercharger, studying the features of its working process, and minimizing losses of the pumped medium is an urgent scientific problem.

2 Literature Review

Ejectors with a vortex mixing chamber have been used for a long time [8, 9], but their main application is the vacuuming of closed volumes [10]. The use of an additional tangential outlet channel in the vortex chamber allows collecting the pumped bulk medium into it and realizing the pumping and operation of such blowers in pneumatic and hydraulic transport [11]. The use of positive displacement pumps for pumping granular materials is usually impractical due to rapid wear and performance deterioration [12, 13]. Hydrodynamic pumps are subject to intense wear, leading to performance and reliability deterioration [14]. In the papers [1, 7], the operation of vortex chamber superchargers is considered. However, the features of pumping bulk cargoes are not considered. Also, no attention was paid to the occurrence of granular materials losses. Experimental studies of the dynamics of the solid particles are complicated due to the rapidity of dynamic processes inside the vortex chamber [15, 16]. Therefore, experimental studies are usually limited to comparing integral indicators [17, 18].

One of the main disadvantages of vortex chamber superchargers is the presence of the pumped medium in the axial drainage channel [1, 7], which reduces the operational efficiency and the supercharger use in hydropneumatic systems. Thus, this paper aims to reduce granular material losses in the vortex chamber supercharger drainage channel. Minimization of losses directly affects the adaptation of resource-saving technologies [19, 20] by increasing the efficiency of pumping bulk cargoes.

Numerical modeling of processes in various devices has been actively developed recently [21, 22], including vortex chamber pumps. CFD (computational fluid dynamics) could track each solid particle pumped by the pump and determine the efficiency of its operation [23]. Modeling the behavior of solid particles in a blower can be carried out based on the approaches of Euler [24] and Lagrange [25]. Since the concentration of solid particles in the supercharger is low, it would be appropriate to use the Lagrange approach. According to this approach, the trajectories of each particle are calculated considering their influence on the primary liquid or gas flow. For these purposes, a three-dimensional model is built [26, 27], a mesh, and a calculation is performed based on numerical methods.

3 Research Methodology

The study was carried out in three stages. First, mathematical modeling of the fluid flow in the supercharger was carried out with the interaction between solid particles based on the calculation of the Reynolds averaged Navier-Stokes (RANS) system of equations [1, 28]. Since the flow simulation led to a vacuum error near the axis, a rotation-curvature correction was included [28]. OpenFoam free open source CFD software was used. The results were compared on three grids: 1 million elements, 2 million, and 7 million. Since the simulation results on grids 2 and 7 million elements differed by no more than 1%, further calculations were made on grids in 2 million items.

In the second stage, an experimental study of the shifting of bulk cargoes was carried out, and the flow rate of material losses in the supercharger drainage channel was measured. In the third stage, the experimental and calculated data were compared with further modeling based on the CFD approach and the development of optimal pumping conditions with the goal function to minimize losses in the drain channel of the supercharger.

The Venturi flow meters and liquid manometers were used for measurements. They made it possible to determine pressures and flow rates with sufficient accuracy. The error in measuring the pressure and flow rate did not exceed 1%. Mass flow rates of bulk medium were measured by weighing the mass accumulated in the corresponding hopper per unit of time, measured by a stopwatch. The error in determining the mass flow rate did not exceed 1%.

4 Results

4.1 Vortex Chamber Supercharger

Figure 1 presents the construction of the vortex device considered in the present study. The vortex chamber supercharger is a mixing chamber with four channels (two axial channels and two tangential ones). The primary flow (water or air) is supplied through the tangential inlet channel and creates a swirling flow inside the chamber with characteristic hydrodynamic flow features: gauge pressure at the periphery of the vortex chamber and vacuum near the axis. The near-axis vacuum creates a differential pressure that facilitates the pumping process. The granular material enters through the inlet axial channel to the vortex chamber, acquires kinetic energy, and also moves to the vortex chamber periphery under the centrifugal force influence. The gauge pressure magnitude at the periphery of the vortex chamber depends on how the second axial channel is used.

It is possible to implement two different work processes depending on the geometric ratio of the tangential and axial channels of the vortex chamber supercharger. The first working process is characterized by relatively high pressure at the periphery and a relatively lower outlet mass flow rate. The second, on the contrary, is a higher flow rate at relatively low pressure at the vortex chamber outlet.

The flow direction in the second (usually lower) axial channel is distinctive of the two pumping work processes. In the first working process, the primary flow is thrown away through the axial channel and forms the loss flow rate. In the second working process, the shifted granular material is sucked through the axial inlet, due to which the

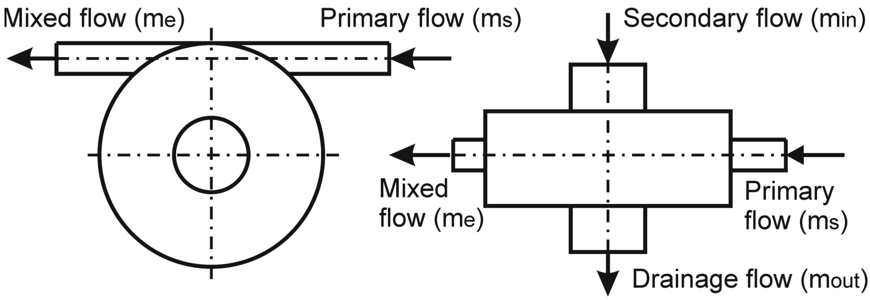

Fig. 1. Vortex chamber supercharger layout.

mass flow rate of the bulk at the pump outlet increases. Thus, the main disadvantage of the first working process implementation is solid particles in the axial (drainage) channel. This paper is devoted to modeling the movement of solid particles in the vortex chamber supercharger and studying the loss flow rate in the drainage channel during the implementation of a working process with the drainage channel.

The second working process without the drainage channel makes it possible to ultimately reduce the losses of the pumped granular materials to zero and change the drainage channel function to the suction channel. But, in this case, the pressure at the blower periphery is significantly reduced, which leads to a noticeable decrease in the energy efficiency of pumping bulk cargoes. Therefore, optimizing the flow rate of the drainage losses while maintaining the working process features allows counting on the higher energy efficiency of the supercharger operation at zero losses of the pumped medium.

4.2 Numerical Simulations

The computational domain and grid model of the vortex chamber supercharger are shown in Fig. 2.

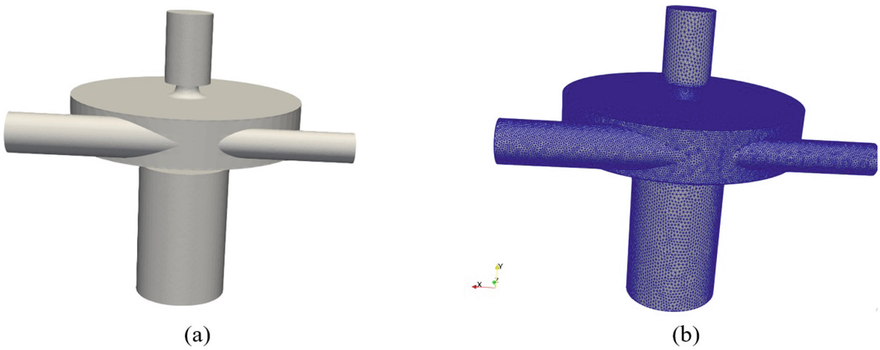

Fig. 2. Schematic of the computational domain for the supercharger: (a) solid model, (b) unstructured mesh used in the present simulation.

The simulation of the trajectories of the solid particles was carried out by the Lagrange method by numerically solving Newton's second law equation, considering particle collisions and wall interaction and the effect of particles affection the gas flow [29–31]. The basic equation used to determine the trajectories of solid particles [32, 33]:

$$x_f = x_i + u_p \delta t$$

where, x_i, x_f are the initial and final position of the solid particle, respectively; u_p is the velocity of the particle; δt is the time step. After completing the calculations at each time step, the new velocity was determined according to the equation:

$$m\frac{du_p}{dt} = \sum F, \tag{2}$$

where m is the mass of the solid particle; $\sum F$ is the sum of all forces acting on the particle. In this study, only the drag force was considered, for a significant reduction in the calculation time, considering the particles affection the gas flow. In the future, it is planned to evaluate the influence of many other forces available in modern software products for modeling solid particles behavior. Information about possible forces acting on the solid particle in gas flows can be found in articles [32].

The flow patterns of the gas and solid phases are shown in Fig. 3. Comparison of the gas flow into the blower with and without solid particles shows that the particle concentration is insufficient for a severe effect of particles on the flow characteristics. The main parameters of the supercharger remain independent of solid particles' presence [1, 7].

The distribution of solid particles by diameter (Fig. 3b and 3c) shows the instantaneous arrangement of particles in the meridional and horizontal planes. The distribution of particles qualitatively confirms the adequacy of the mathematical model and corresponds to the instantaneous flow patterns observed in the experiment. As a result of the calculation, the mass flow rates of solid particles passing through the boundary conditions were determined, making it possible to compare the mass flow rates with the experiment.

Using particle trajectories mathematical modeling in the supercharger, it was possible to determine the pumped medium's mass flow rate of losses. The flow rate was determined by calculating the number of particles entering the drainage channel about the total amount of solid particles. The simulation results were verified by experimental studies. Reducing losses allows for improved industrial design and efficiency of supercharger applications.

4.3 Experimental Results

An experimental plant was created for studies of the bulk cargoes pumping, which made it possible to measure the mass flow rates of the granular material, as well as the main parameters of the blower by measuring the pressure and flow rate of the gas in each channel.

Experimental studies have made it possible to confirm the adequacy of mathematical modeling based on a comparison of the loss of solid particles in the drainage channel.

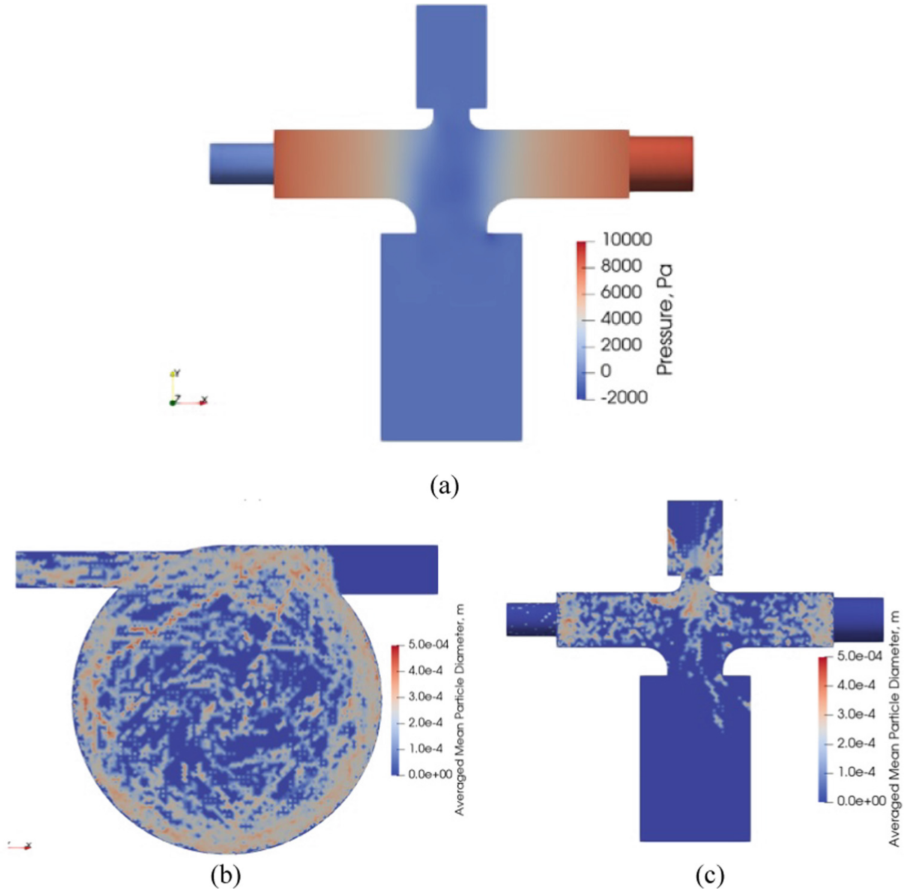

Fig. 3. Simulation results: (a) pressure contours of the pump flow field; (b) solid particles in the horizontal plane; (c) solid particles in the meridian plane.

Increasing the primary flow dynamic pressure leads to a decrease in the losses in the drainage channel (Fig. 4). At dynamic pressure of more than 5 kPa, the simulation results were in excellent agreement with the experiment. However, such a mode of operation of the blower with low dynamic pressures and, accordingly, with small swirl numbers is not rational and is usually not used. There are minimal losses of the secondary flow if the solid particle density is 2000–3000 kg/m^3. Density values with a minimal mass flow rate ratio of losses are explained by the peculiarities of energy transfer to the pumped particle. With an increase in density, the particle does not have time to gain speed and begin to rotate near the vortex chamber axis, which leads to the particle falling into the drainage channel. The decrease in losses can be the increase in the vortex chamber height or the setting of a rotary motion to a particle in the inlet hopper.

The increase in the vortex chamber height can worsen the energy characteristics of the blower operation and its efficiency; therefore, it is more promising to create rotational flow at the chamber inlet, for example, using a vane swirler.

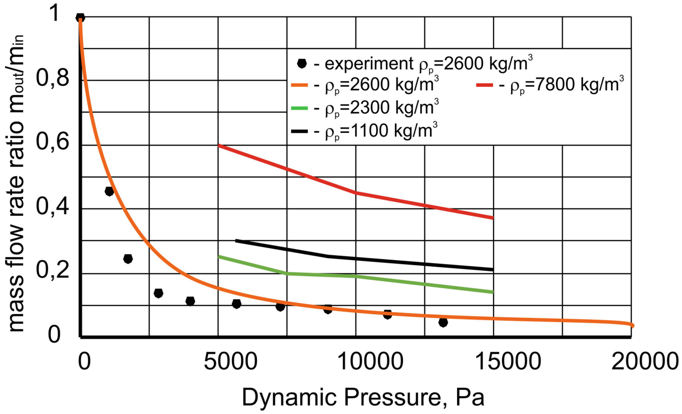

Fig. 4. Effect of the dynamic pressure and solid particle density on drainage mass flow rate ratio (m_{out} is the drainage mass flow rate and m_{in} is the inlet mass flow rate).

The future is being planned to create an autonomous installation for the transportation of bulk cargoes based on solar batteries [34, 35]. This opens the possibility of widespread use of such systems in many industries. This installation will have a minimum drainage flow rate.

5 Conclusions

Numerical simulations of the gas-particle two-phase flow in the vortex chamber supercharger were conducted. The mass flow rates of the solid phase in each channel were determined.

Experimental studies confirmed the adequacy of the CFD results. The value compared the flow rate in the supercharger drainage channel. At dynamic pressures of more than 5 kPa, the simulation results agreed with the experiment. The maximum calculation error is observed at low values of the dynamic pressure at the supercharger inlet.

The solid particle density with a minimal mass flow rate ratio of losses should be in the range of 2000–3000 kg/m^3 for the investigated vortex chamber supercharger.

An increase in the primary flow dynamic pressure makes it possible to reduce the losses of the pumped medium in the drainage channel by 50% with a twofold increase in the dynamic pressure.

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