

# Development and application of vortex control valves in pneumohydraulic systems

A Uss<sup>1,3</sup>, A Pugachuk<sup>1,2</sup> and A Chernyshov<sup>1</sup>

<sup>1</sup>Bauman Moscow State Technical University

<sup>2</sup>United Institute of High Temperatures of Russian Academy of Sciences, Moscow, Russia

<sup>3</sup>E-mail: [uss25.ru@mail.ru](mailto:uss25.ru@mail.ru)

**Annotation:** The current state of the development and study of vortex jet devices that are used as control valves based on the working medium vortex flow principle is reviewed and analyzed in the article. The scientific and technical literature is reviewed. The article considers vortex valves without mechanically moving parts, as well as a semi-mechanical vortex valve. The principle of operation of a vortex jet device is described. The rationale of the use of a vortex jet device as an actuator in a valve for controlling the flow of a working medium, as well as in a control system of a sleeve-valve cylinder, is given. The classification of vortex jet devices by the feed type of the supply and control flows of the working medium is carried out for the first time.

## Introduction. Actuality

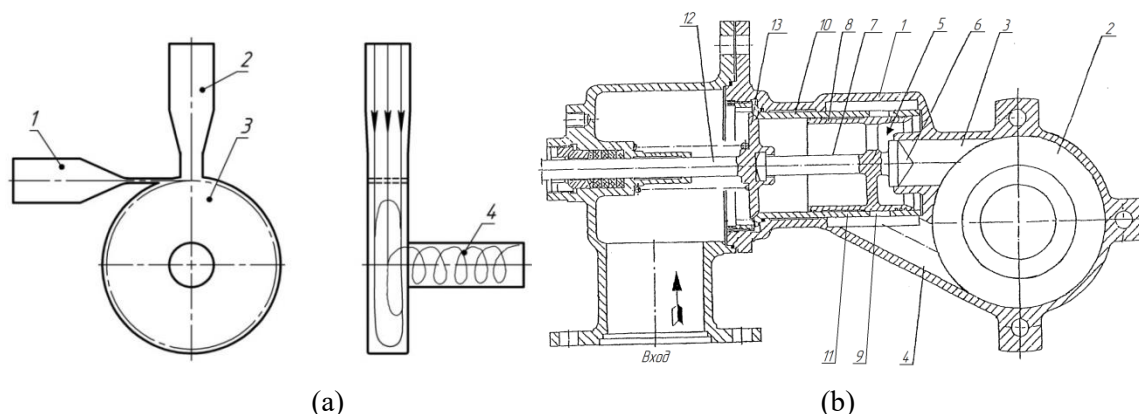
Nowadays, devices designed to control the flow of the working medium (WM) are widely used in many areas of practical human activity. The working medium is to be understood as compressible and not compressible Newtonian viscous fluids. This class of devices is usually called block-and-regulating devices (BRD). BRD include valves, faucet, cutoff plates, butterfly dampers, pressure or flow WM regulators, etc. This paper will tell about vortex valve as one of the crucial elements in a pneumohydraulic system. Being an automatic device the valve includes such basic elements as actuating unit and drive component. Such type of valves refers to mechanical valves. The object under consideration is the regenerative stage with a pressure pipe and a separator.

Valves largely determine the reliability and faultless performance of the pneumohydraulic systems in which they operate. First of all this can be explained due to the presence of elements, that move at high speeds and collide with parts and components of the configuration. The moving elements of the valve are exposed to non-linear gas-static and gas-dynamic loads. The valve parts are in interaction with the flow of the working fluid with a high speed under the influence of which a partial and in certain cases complete destruction of the sealing element is possible. The use of mechanical valves in systems with contaminated, aggressive and/or high-temperature mediums is extremely difficult and commonly simply impossible.

Regulating and shut-off valves constitute a significant part of the controlling the multiphase flow equipment in modern industry, power plants, mining, in the pneumohydraulic sections of various mechanisms, etc. They can be used to maintain the given flow rates at a constant high resistance as well as to change the resistance and flow rate by moving or turning the element of the final adjustment of the system in accordance with a given program.



It is possible to increase the reliability of the BRD by creating construction designs without moving elements. The operating principle of which is based solely on gas-dynamic effects such as the Coanda effect, turbulization of the WM flow as well as the use of the swirl flow of the WM. Devices that use the listed processes and effects to control the WM flow are called “vortex jet devices” and can be used as an actuation device. The classical scheme of the vortex jet device is shown in (Fig. 1a).



**Figure 1.** (a) — vortex jet device switching circuit; (b) — application of a vortex jet device in a semi-mechanical vortex control valve.

The operating principle of the vortex jet device (hereinafter VJD) shown in Figure 1a is as follows: the power flow enters the channel 2, then into the vortex chamber 3, fills it and passes to the outlet pipe 4. If it is necessary to lower the pressure/flow rate in the outlet pipe 4 an auxiliary stream — control stream must be supplied to the control channel 1. As a result of the interaction between the supply and control jets, they merge so that the mass of the resulting stream represents the sum of the masses of the individual jets. The direction of the resulting flow is determined by the geometric sum of the number of motions of the colliding flows.

Bugaenko V.F. in [1] suggested to introduce the following notation:  $\alpha$  — angle of deviation of the supply stream,  $\beta$  — angle between the axes of the supply and control channels  $I_1 = F_1 v_1^2 Q$  — momentum of the force of the control flows,  $I_0 = F_0 v_0^2 Q$  — momentum of the power of the supply flow.

Then the equation describing the deviation of the resulting flow can be represented as

$$\alpha = \eta \arctg \frac{(I_1 / I_0) \sin \beta}{1 + (I_1 / I_0) \cos \beta}, \quad (1)$$

where  $\eta$  — deviation coefficient of the resulting jet from the original direction of the supply jet. It is known that for vortex controllers having channels with a circular bore  $\eta \approx 0.8$  from the scientific and technical literature. Formula (1) is based on the assumption that the static pressure is constant in the field of interaction of the jets and that the velocity distribution over the cross section is uniform in the supply channels and in the resulting stream.

After the interaction of the supply and control flows the resulting flow under the influence of the Coanda effect adheres to the cylindrical wall of the vortex chamber. As a result of this, a vortex flow of the working medium is formed in the vortex chamber. The main principle of reducing the pressure in the outlet pipe is to create significant hydraulic resistance during the spiral movement of the working medium from the periphery of the vortex chamber to the center. The resistance is due to the vortex flow, which results in the formation of a field of centrifugal forces acting on the rotating mass of the working medium. Under the influence of centrifugal forces, the working medium is discarded to the periphery of the vortex chamber. As a result of this, a pressure drop is created: in the center of the

vortex — reduced pressure; at the periphery of the vortex — increased pressure. At that moment, when the pressure at the periphery of the vortex chamber becomes equal to the pressure in the power channel, the flow from the power channel stops. This effect is called the effect of blocking the supply flow in the vortex jet device.

Based on the principle of operation of the VJD, we can conclude that the main purpose of the control flow is to reject the supply flow by  $90^\circ$  to form a vortex flow of the working medium in the vortex chamber of the VJD.

Analyzing the formula (1), we can conclude that to deviate the supply flow, the control flow should have a larger momentum of force compared to the momentum of the supply flow.

The deviation of the power flow is constructively provided as follows:

1. by making the design of the passage section of the control channel smaller than the passage section of the power channel, whereas it is necessary to increase the pressure in the control channel to increase the momentum of the control flow force;
2. by making the design of the control and supply channels with equal through sections, while the pressure and flow rate in the control channel remain equal to the pressure and flow rate in the power channel. In this configuration, the blocking effect is not possible, and the vortex jet device will act as a vortex choke. The considered concept was implemented in [2,3].

The relevance of the development of control devices using the principle of the vortex flow of the working medium is confirmed by many developments of similar products in various fields of technology. Let us consider the most significant developments that use the vortex valve in hydraulics.

The analysis of existing problems in hydraulic control equipment for multiphase transport pipelines of high pressure and flow shows that the development of a new valve capable of providing high hydraulic resistance (about 30-40 MPa and even more if necessary) is currently a serious task. All valves designed for high pressures are subjected to cavitation, severe erosion and, as a result, shortened device service life.

Throttling of the fluid flow at large pressure drops is usually accompanied by cavitation. The fluid passing through the throttle element of the control valve experiences changes in speed, since it enters a narrow constriction of the valve body (increase in speed) and then enters the expanding region of the valve body downstream after the throttle section (decrease in speed). These changes in velocity likewise lead to a change in the kinetic energy of the liquid molecules. To save energy in a moving fluid stream, any increase in kinetic energy due to an increase in velocity is accompanied by an additional decrease in potential energy, usually in the form of a liquid pressure. It indicates that the fluid pressure decreases at the point of maximum restriction in the valve, then again increases (or recovers) downstream after the throttling section. As long as the working medium is not a compressible liquid, and the pressure at the point of maximum narrowing is less than the saturated vapors pressure of this liquid at the flow temperature, the liquid will spontaneously boil. If the pressure is restored to a point above the vapor pressure of the liquid, the vapor will again condense into the liquid. This phenomenon is called cavitation. In case of cavitation appears close to the surface of the part, erosion may occur, what ultimately will lead to the leakage of the valve assembly, and subsequently to the destruction of the entire structure.

One of the technical solutions that can effectively deal with cavitation are valves based on the principle of the vortex flow of the working medium (Fig. 1b). The vortex valve has improved cavitation characteristics, is easy to manufacture. It can operate reliably in an almost unlimited range of pressure drops and high temperatures.

Vortex valves typically have at least one radial inlet channel and one or more tangential control channels. The supply pressure should be kept constant for optimal modulation of the flow rate at the outlet, and the control pressure should be 1.2-2.0 times higher than the supply pressure at the minimum flow rate.

New vortex valves in which the interaction of opposite tangential flows is used appeared to eliminate the above (Fig. 1b). The vortex movement allows creating a pressure gradient inside the vortex chamber, because of which the gas bubbles are displaced to the center of the vortex flow (at a

distance from the structure wall). That excludes direct contact of pulsating and collapsing bubbles with the valve working surfaces, prevents the formation of erosion and thereby prolongs the service life devices.

The flow is not twisted and its resistance is minimal at the same flow rates through the tangential channels of the vortex chamber. When closing the supply pipe to one of the channels, the flow swirl increases, as well as the hydraulic resistance to the flow passing through the valve.

Constructively the valve comprises a housing 1 with a vortex chamber 2, inside which tangential channels 3 and 4 create opposite flows. The housing contains a sleeve 10 with via-holes 9 for the passage of the working fluid from the inlet chamber to the tangential channel 4. The regulating element 5 is installed in the housing coaxially to the channel 3. Element 5 consists of a cylindrical shell 8 and a central shaft 7 with a shaped head 6 interconnected by ribs 11. The rod of the regulatory element is connected to the drive shaft 12.

When the control element is moved by the drive shaft 12, the channels 9 begin to close, which ceases the equality of flows through channels 3 and 4 and creates a rotating flow in the vortex chamber, thereby increasing the hydraulic resistance of the valve. When all the supply channels are closed, the further movement of the regulating element brings its contour head into interaction with the entrance to the channel 3, further increasing the valve resistance. The required valve flow characteristic is ensured by designing via-holes in sleeve 10 and stem head 7.

Thereby, the operation of such a vortex valve does not require a control flow with a higher pressure level. The distribution element is installed on the pipeline through which not more than half the flow rate of the working fluid is supplied.

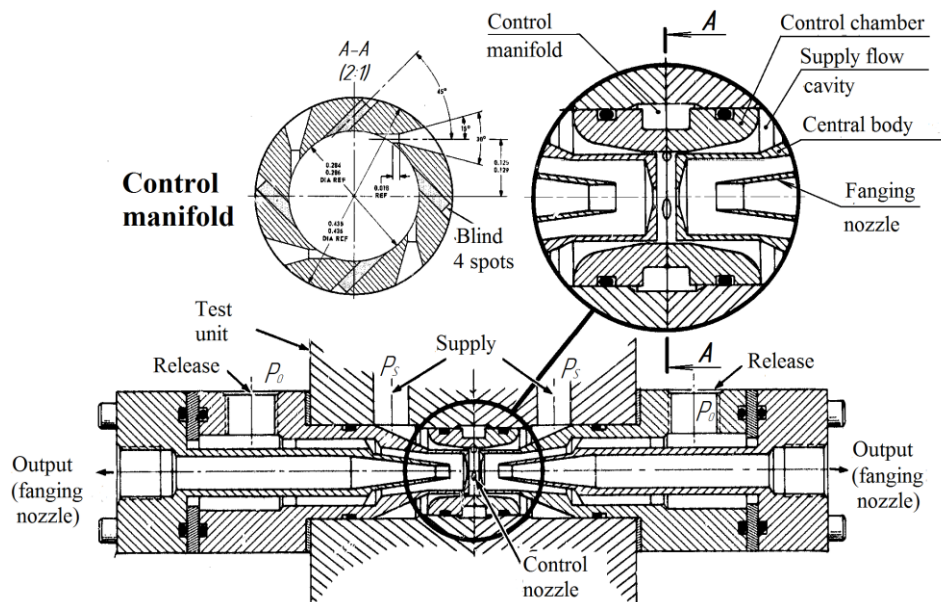
Vortex jet devices can be used to control the thermodynamic parameters of high-energy WM flows, which include high enthalpic WM flotation, as well as high-flow WM flows.

A vortex valve scheme with a distributed supply of feed and a concentrated supply of working medium control flows was proposed in [4] (Fig. 2). Constructively the valve consists of a test unit, a control chamber, two central bodies, two receiving nozzles. The vortex chamber of the valve is formed by the following surfaces. The end walls of the vortex chamber are formed by the end surfaces of the central bodies, the cylindrical wall of the vortex chamber is formed by the cylindrical surface of the control chamber. The vortex valve principle of operation is following. The working power medium enters the cavity of the supply flow, then it is distributively feed through the annular gap between the central body and the control chamber. The control flow is supplied to the control collector, then through the tangentially located control channels into the vortex chamber, where it interacts with the supply flow. As a result of this, a vortex flow of the working medium is formed in the vortex chamber of the valve. As a result of the formation of a vortex flow at the exit of the vortex chamber, the torch is defocused, thus the working medium moves along the cone, surrounds the "receiving nozzle" part and enters the discharge channel. In the absence of a supply stream, a vortex flow is not formed and the working medium when it flows out of the vortex chamber represents itself a flooded stream, thus entering the receiving nozzle and then into the outlet pipe.

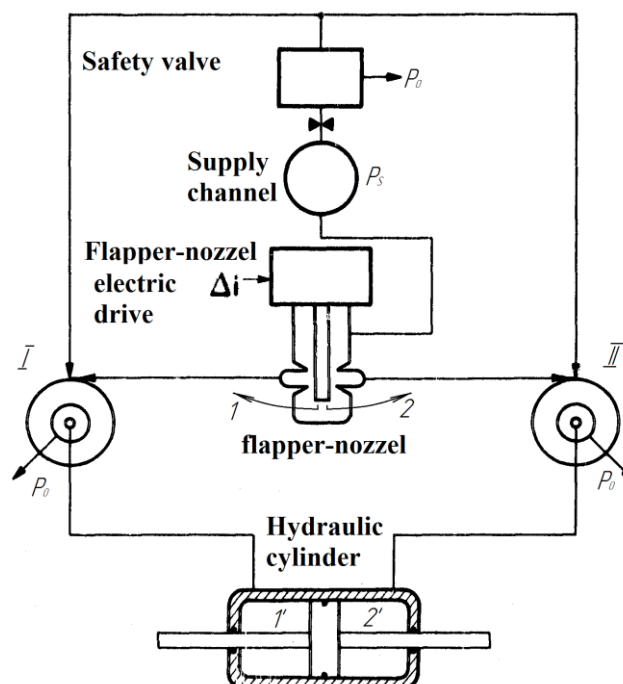
The vortex valve developed in paper [4] is proposed to be used in the control system of the hydraulic cylinder. Conceptually the hydraulic cylinder control scheme (Fig. 3) consists of a pilot stage representing itself an electric drive with a flapper-nozzle, which provides flow control for two vortex valves I and II. These valves are part of the hydraulic cylinder control power stage. Power stage vortex valves are configured with a hydraulic cylinder.

The servo valve hydraulic circuit diagram is shown in Fig. 3. The supply flow from the flow driver doubles and enters the power channels of the vortex valves I and II. The pilot stage flapper-nozzle operates as follows. The control flow from the flow driver enters the working cavity of the damper nozzle. When the shutter moves in the direction 1, the left nozzle closes and the right nozzle opens, thereby the fluid enters the control channel of the vortex valve II, locking it, while the vortex valve I opens. Thus, the liquid with higher pressure enters the cavity 1 of the hydraulic cylinder, the pressure drop acting on the piston induces a force acting in the direction from the cavity with higher pressure to the cavity with lower pressure, as a result of which the piston with the rod moves to the right. Fluid is

forced from the right cavity of the hydraulic cylinder to the discharge channel of the vortex valve II. In a similar manner, the piston moves with the rod to the left.



**Figure 2.** Vortex servo valve with distributed feed and concentrated feed of working medium control flows.

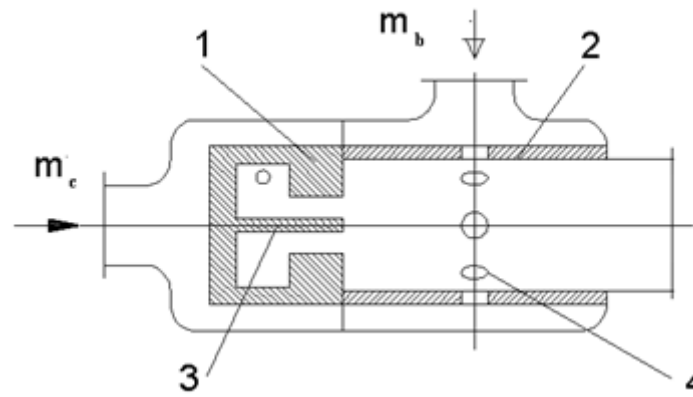


**Figure 3.** The scheme of the hydraulic cylinder control by means of vortex valves.

The design of a vortex valve with a concentrated feed of the supply and a distributed feed of the control flows of the working medium was proposed in [5] (Fig. 4).

A circuit diagram of the proposed vortex valve is shown in Figure 4. The device contains a vortex chamber 1 with tangential channels or holes for the control flow input and nozzle at the outlet of the

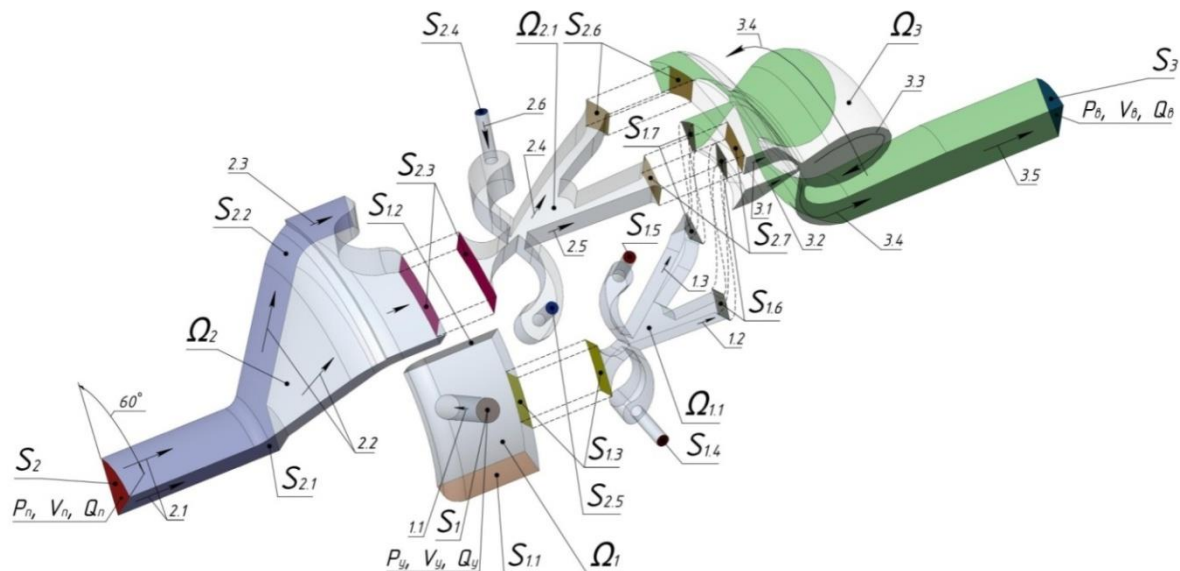
common cavity. The adjustable flow is supplied to the sleeve 2 and through a series of radial channels 4 enters the common cavity, where it interacts with the control flow before exiting the device. The diameter of the nozzle of the vortex chamber is designed large to approach the vortex control flow to the exit from the radial channels and rod 3 is installed to maintain nozzle cross section.



**Figure 4.** Scheme of a vortex valve with a concentrated supply and distributed feed of control flows of the working medium.

The reviewed vortex valves designs can be used to control the flow of a compressible fluid as well as to control the thermodynamic parameters of high-energy flows of WM, which include high-enthalpy flows of WM, and flows of WM with high pressure and flow-rate.

The author of this work proposed the design of a vortex valve [6] with a distributed feed of supply and control flows of the working medium (Fig. 4).



**Figure 5.** The calculated area of the vortex valve with a distributed feed of supply and control flows of the working medium, as well as with the possibility of twisting them (cutout 5/6).

The operating principle of the gas pressure regulator with a distributed feed of the supply control flow of the working gas and with the twist control of the supply and control flows, as well as the operating principle of the pressure regulator with the concentrated feed of control and supply flows, is based on the principle of interaction of the jets. However, in this design, the power supply 2.1 through section  $S_2$  enters the supply pipe, then flowing around the central body enters the collector of six

triggers  $\Omega_{2,1}$ . Arrows 2.1-2.2-2.3 indicate the gas flow in the supply channel. Trigger  $\Omega_{2,1}$  works as follows: when the working fluid is supplied to section  $S_{2,4}$  (under pressure equal to the supply pressure), flows 2.3 and 2.6 interact, and as a result, the resulting stream moves in the radial direction 2.5. The working medium (under pressure equal to the supply pressure) is supplied to section  $S_{2,5}$  to deviate the feed stream in the tangential direction. As a consequence of this, the flows 2.3 and 2.5 interact and the resulting stream 2.4 moves in the tangential direction. Hereafter the working stream 3.1 is fed into a vortex toroidal chamber, where it interacts with the control flow 3.2. The control flow, as well as the supply flow, can be pre-twisted with the help of a collector of six triggers  $\Omega_{1,1}$  on the control channel. The operating principle of the control collector is similar to the principle of the collector installed on the power supply. To feed the control flow 1.1 in the radial direction, the working fluid (under pressure equal to the control pressure) is fed into section  $S_{1,5}$ , to feed the control flow in the tangential direction; the working fluid is fed into section  $S_{1,4}$ . A complex spiral-like flow of the working fluid is formed in the interaction of the supply 3.1 and the control 3.2 flows of the working medium in the vortex toroidal chamber. As a result of it a pressure gradient is created in the vortex chamber: the minimum pressure at the center of the vortex and the maximum at the periphery of the vortex. The pressure of the working fluid at the periphery of the vortex if reached equal to the supply pressure, the decrease in the power consumption up to its closure appears.

The mathematical relations of the output parameters (pressure and flow rate at the device outlet) on the control parameters (pressure and flow rate in the control channel), as well as the influence of changes in the geometric parameters of the flow cavity (vortex chamber diameter  $D$ , vortex chamber width  $H$ , geometric parameters of the power and control channels their number and location) on the change in the value of thermodynamic parameters are described in [7–9]. The presented mathematical models were based on empirical dependences, in other words on the data of experimental studies. That practically can only be applied in a narrow range of thermodynamic parameters of WM and at the initial stage of calculation of similar structures.

Modern studies of the article's authors on the VJD: a patent review, a scientific and technical literature review, a design of vortex valves review, identifying of the advantages and disadvantages, a numerical study of gas-dynamic processes in the flow chamber of the VJD in distributed gas-dynamic parameters, an investigation of the effect of locking the feed channel as well as creating of a design, a series of experimental studies and verification of the mathematical model of the workflow are described in [10–13].

### Classification of vortex valves according to the type of feed of the supply and control flows of the working medium.

As a review of the state of the issue on the development of vortex valve designs shows, currently there are many designs of the supply and control flows feed to the vortex chamber. That leads to a variety of vortex valve designs. Relative to it there is a need to classify structures according to the type of feed of the supply and control flows of the working environment.

By the type of feed of the working medium is meant the organization of the supply of the working medium to the vortex chamber of the vortex jet device. Concentrated feed - when the working medium is supplied through the channels in the form of nozzles. Distributed feed - when the working medium is fed through annular channels around the entire perimeter of the vortex chamber.

Vortex jet devices in general can be represented by the type of feed of the working medium in the form of a matrix of possible design options: the columns of which display channels (supply and control), and the line type of feed: concentrated and distributed. The numbers indicate the intersection of rows and columns.

FeedFlow \	Supply	Control
Concentrated	1	2
Distributed	3	4



- 1-2 with concentrated feed of the supply and control flow of the working medium. The number of power and control channels located around the perimeter of the vortex chamber can be different 1, 2 ... n supply and control channels. An example of such constructions can be found in [7,8];
- 3-2 with distributed feed and concentrated feed of the control flow of the working medium. There are known vortex jet devices [4], where the feed of the supply flow is organized in a distributed manner (the working medium flows around the central body and through the annular channel enters the vortex chamber), and the control flow is concentrated through the nozzles located around the perimeter of the vortex chamber.
- 1-4 with concentrated feed of the supply flow and distributed feed of the control flow [5].
- 3-4 with a distributed feed of supply and control flows of the working medium [6].

### Conclusion

An analysis of the research conducted in this area and a review of existing technical solutions allows us to formulate the following conclusions:

- designs of control valves using the principle of the vortex flow of the working medium are considered. Their widespread application confirms the relevance of the development of such devices, and the legitimacy of their use to solve technical problems;
- analysis of technical solutions showed the advantage of vortex jet devices (high reliability, the ability to work with various working fluids, including working fluids with abrasive inclusions, low manufacturing costs, low operating costs, immunity to radiation and electromagnetic fields), which is why it is recommended to use a vortex jet device as an actuator in valves;
- the first classification of vortex jet devices according to the type of feed of the supply and control flows of the working medium;
- the article is a scientific source for further work on the development and study of vortex control valves [14–21].

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