INTERNATIONAL JOURNAL OF RESEARCH AND SCIENTIFIC INNOVATION (IJRSI)
ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue IX September 2025

Analysis of Power (Energy) Losses on Spool Valves of Hydraulic Mining Machines

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DOI: https://doi.org/10.51244/IJRSI.2025.120800374

Received: 12 Sep 2025; Accepted: 19 Sep 2025; Published: 16 October 2025

ABSTRACT

The world's leading manufacturers of hydraulic equipment: Boschrexroth, Atos, PONAR Wadowice, etc. are constantly working hard to improve the design of hydraulic equipment. In recent years, the quality of hydraulic equipment, including hydraulic valves, has been significantly improved. But still, the efficiency of hydraulic equipment, in terms of energy losses, leaves much to be desired. By such an important indicator as efficiency factor, the hydraulic drive of mining machines is much inferior to the electric drive.

The paper presents an analysis of one of the main elements of the control system of hydraulic drives - the hydraulic distributor. Using the example of the most widely used typical spool distributor, it is shown that energy (pressure) losses in hydraulic distributors occur due to vortex formation (turbulence) in separate parts of the hydraulic distributor. The cause of vortex formation is sharp changes in the cross-section of the liquid flow (contraction, expansion), as well as the presence of sharp changes in the direction of the flow. All these factors are well illustrated in the KompasFlow programme, which is based on computational fluid dynamics and is a version of the FlowVision software package integrated into KOMPAS-3D as an application. Visualisation layers show specific sections of the hydraulic distributor in which there are changes in flow direction, pressure and velocity values, and areas of turbulence. Visualisation of the fluid flow in the spool hydraulic distributor clearly confirms the fact that the currently existing designs of hydraulic distributors do not allow to exclude completely or minimise the number of vortex formation zones.

It is necessary to create a new design of the hydraulic distributor operating on other, different principles from the existing one. The new design of the distributor should completely exclude or minimise the number of zones of possible turbulence occurrence and provide a corresponding reduction in energy (pressure) losses on the hydraulic distributor. The obtained results of the research can be used in real production.

Keywords: hydrofitted mining machines, hydraulic drive, hydraulic distributor, pressure losses, KompasFlow, express analysis.

INTRODUCTION

Machines are now an integral part of our daily lives. Machines are used in a wide variety of industries and in everyday life. They facilitate work and increase its productivity.

Any machine can be represented as a sequential combination of three components: a drive motor, an executive mechanism, and a drive.

It is obvious that the efficiency of any machine can only be ensured if each of these three elements works as efficiently as possible.

The overall efficiency (efficiency factor) of a system of sequentially connected mechanisms is equal to the product of the efficiency factors of these mechanisms. In our case, the overall efficiency of the entire machine will be equal to the product of the efficiency of the motor, drive and actuator:

$\eta_o = \eta_d \cdot \eta_p \cdot \eta_{e.m.}$

In turn, the drive is a rather complex system consisting of other smaller elements.

Therefore, the efficiency of the drive also depends on the efficiency of its smaller components. For example, the overall efficiency of a hydraulic drive is the product of the efficiencies of all its components: filter, pump, safety valve, distributor, throttle, etc. Low efficiency of any of these components significantly reduces the efficiency of the entire drive.

Currently, for an optimally designed hydraulic system, the overall (total) efficiency is usually between 0.65 and 0.75.

In modern electric drives, the efficiency is in the range of 80-90%. For special machines, modern technologies allow the efficiency to be increased to 96%.

Thus, despite the fact that hydraulic drives have significant advantages, such as:

1. High specific power of the hydraulic drive, i.e. the transmitted power per unit of total weight of the elements. This parameter is 3-5 times higher for hydraulic drives than for electric drives;
2. Relatively simple stepless speed control of the output link of the hydraulic drive over a wide range;
3. High speed of the hydraulic drive, due to the low moment of inertia of the hydraulic motor's actuator (the moment of inertia of the rotating parts of the hydraulic motor is 5-10 times less than the corresponding moment of inertia of an electric motor);
4. Simplicity of converting rotary motion into reciprocating motion.

All these advantages of the hydraulic drive are offset by a single disadvantage – low efficiency. This explains why electric drives are predominantly used in modern machines and mechanisms

METHODS

A large number of scientific works are devoted to the study of energy losses in hydraulic drive mechanisms and issues of improving the energy parameters of hydraulic machines.

According to the results of studies [1-4], it has been established that when hydraulic machines are in operation, the useful use of energy is 51%. Consequently, energy losses are about 49%.

The research results also showed that when hydraulic machines are in operation, the greatest losses occur in hydraulic distributors [5-6], in the process of throttle control of working speeds (20%) and in primary safety valves (17.2%). Losses are significantly lower in drain hydraulic lines (7.5%), actuators and secondary safety valves (4.3%).

The results of an analysis of previous studies show that modernising the design of hydraulic pumps, hydraulic cylinders, hydraulic motors and hydraulic lines does not yield significant positive results in terms of reducing energy losses, although it does lead to some useful improvements [9-14].

Thus, research into reducing energy losses in distributors will make it possible to significantly increase the overall efficiency of the entire hydraulic drive of machines.

Let us consider the energy losses that occur when fluid passes through spool valves, since such valves are used in the vast majority of hydraulic circuits.

The principle of operation of spool hydraulic distributors was considered using the example of a four-line, three-position distributor, Fig. 1 [15].

In the initial position, the spool of the valve is in the middle position (position) under the action of springs, all four lines (two supply lines P and T, and two outlet lines A and B) are closed. When electrical voltage is applied to the right electromagnet, the spool shifts and compresses the right spring. In this position, the supply pressure line P is connected to the working line B, and the drain line T is connected to line A. When the solenoid is deactivated, the spool returns to its initial position under the action of the compressed spring. When voltage is applied to the left solenoid, the spool shifts to the left, compressing the left spring and connecting lines T - B and lines P - A.

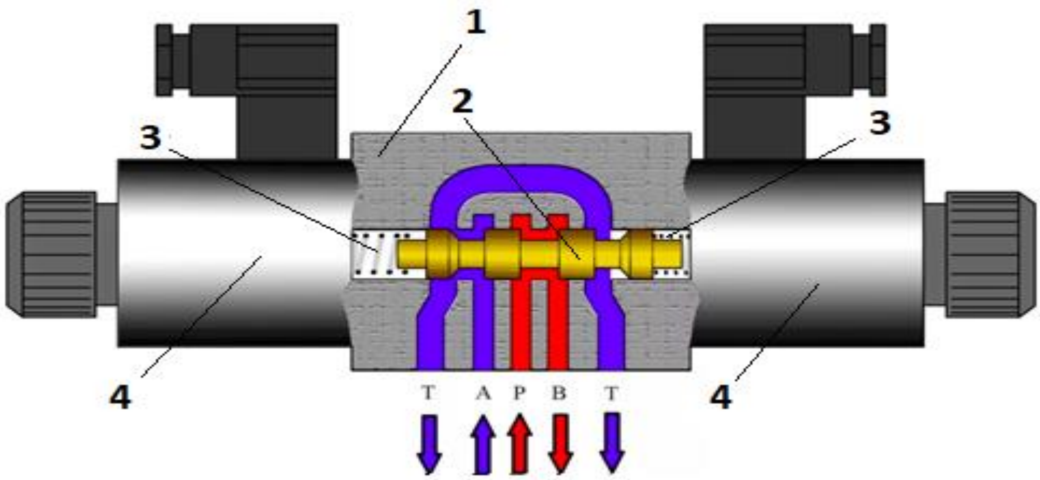


Figure 1. Principle of operation of a three-position, four-line hydraulic distributor: 1 – body; 2 – spool; 3 – springs; 4 – electromagnet

Previous studies show that the critical Reynolds number for spool valves is Re = 100-250, and therefore the fluid flows in the valves are predominantly turbulent. Accordingly, the pressure losses Δp in the valves are very close to a parabola.

Pressure losses in the hydraulic distributor, which occur mainly due to vortex formation in individual parts of the hydraulic distributor, can be determined by the dependence [16,17]:

$$\Delta p = \zeta \cdot \rho \cdot \frac{V^2}{2},$$

where V is the fluid velocity, m/s; ρ is the density of the fluid, kg/m^3 ; ζ is the resistance coefficient;

The value of ζ for spool valves usually ranges from ζ = 3 to 5.

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue IX September 2025

However, the analytical dependencies given can only be used for approximate calculations of hydraulic systems. For accurate calculations, additional experimental tests (flow tests) of specific distributors under real operating conditions are required. Graphical dependencies of pressure losses are usually given in the technical characteristics of the product. For example, graphical dependencies of pressure losses Δp in electrically controlled spool valves type WE10...12/... with different circuits, presented by PONAR Wadowice, a leading Polish manufacturer of hydraulic components and systems [9], are shown in Fig. 2.

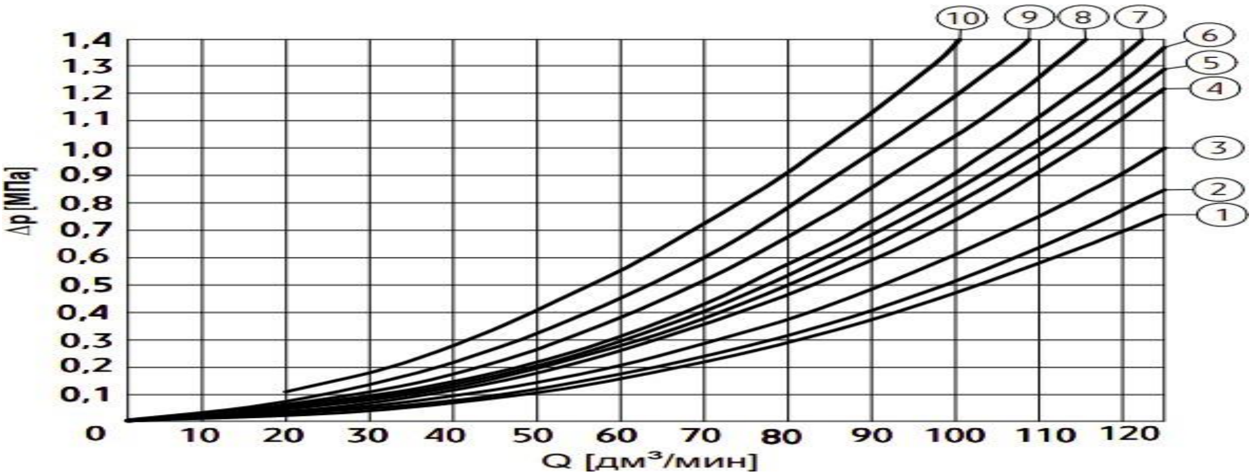


Figure 2. Dependencies of pressure losses Δp in electrically controlled spool valves of the WE10...12/... type with different circuits (1-10).

The graphical dependencies shown allow us to estimate how pressure losses in the distributor change depending on the flow rate and design scheme.

Let us consider, as an example, two extreme cases: the type WE10...12/... distributor designed according to scheme 1 and the distributor designed according to scheme 10.

At a working fluid flow rate of 100 dm^3 /min, the pressure losses are: for scheme 1 – 0.47 MPa; for scheme 10 – 1.4 MPa.

When the working fluid flow rate through the distributor is halved (50 dm^3/min), the corresponding losses are only 0.1 MPa and 0.4 MPa, respectively.

We can see that when the flow rate is halved, the pressure losses decrease and the efficiency increases accordingly. For a distributor designed according to scheme 1, the losses are reduced by 4.7 times, and for a distributor designed according to scheme 10, by 3.5 times.

However, the above theoretical calculations do not provide a complete and comprehensive picture of the causes of energy loss and efficiency in hydraulic distributors.

It was noted above that losses mainly occur due to vortex formation in certain parts of the hydraulic distributor. However, neither analytical dependencies nor graphical representations provide answers as to where exactly these vortices occur, why they occur, and what can be done to eliminate them.

At the same time, there are now programmes that allow you to visualise the movement of fluid in various elements of the hydraulic drive, including hydraulic distributors. With the help of such programmes, designers can visually identify specific areas in the hydraulic distributor where energy losses occur and make design decisions to eliminate or reduce these losses.

One such programme is Kompas Flow. Kompas Flow is based on a discipline called computational fluid dynamics and is a version of the Flow Vision software package integrated into KOMPAS-3D as an application [10].

In the Kompas Flow system, the calculation domain is the volume of fluid inside the pipeline elements. Therefore, for the calculation, it is necessary to use standard KOMPAS-3D tools to select the volume of fluid inside the hydraulic distributor housing as a separate closed volume. The calculation area may also contain the volumes of streamlined bodies (in our case, the spool) [11].

Results. Since the principle of operation of all spool hydraulic distributors is the same, the simplest, two-line, two-position hydraulic distributor was taken as the object of study.

The principle of operation of a two-position, two-line hydraulic distributor is shown in Fig.3 [6].

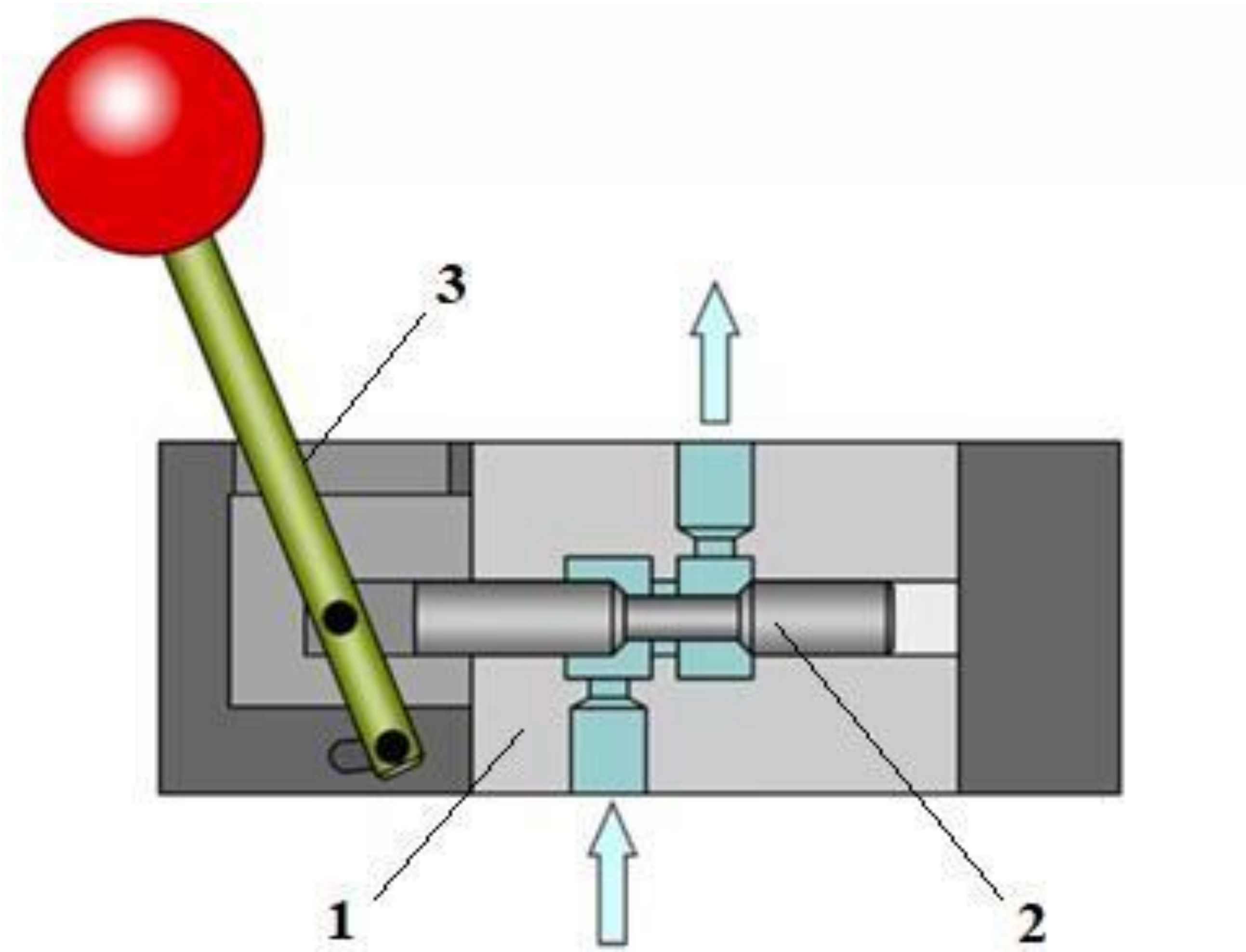


Figure 3. Principle of operation of a two-position, two-line hydraulic distributor: 1 – body; 2 – spool; 3 – control lever When the control lever is in the position shown in Fig. 3, the pressure line is connected to the working line. When the control lever is moved to the right, spool 2 moves and disconnects the channels.

Figure 3 shows that in order to get from the pressure line to the working line, the fluid has to overcome several turns at different angles, areas of expansion and narrowing of the flow. Naturally, overcoming these sections leads to energy losses and reduced efficiency.

For a quick analysis of the hydrodynamics of the device and visualisation of the fluid flows passing through the spool distributor, the Kompas Flow software package was used. It has a simple interface for quick analysis of devices and is used in the early stages of product design.

For an initial assessment of the impact of design decisions in the geometry of the device on its efficiency, we will isolate a separate closed volume of fluid in the distributor housing (Fig. 4) moving from the pressure line P to the working line B and consider the nature of changes in parameters such as the speed of movement and pressure of the fluid flow along the entire path from the supply pressure line P to the working line B.

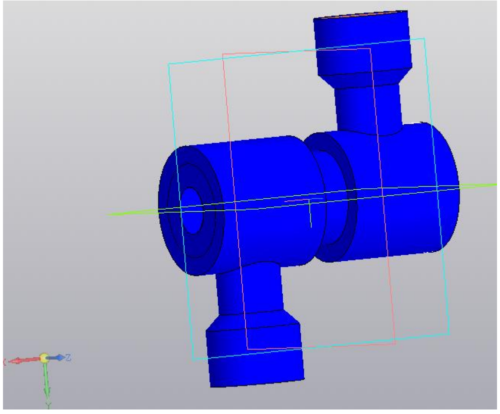
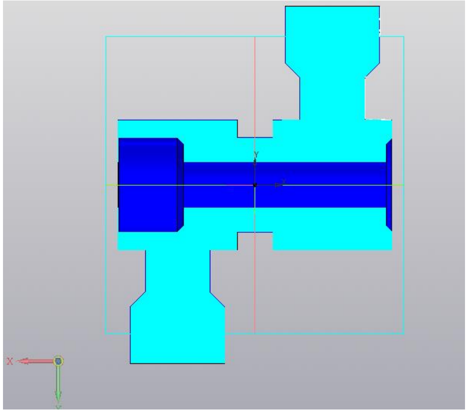
a  b 

Figure 4. Isolated fluid volume in the hydraulic distributor: a – general view; b – cross-section in the XOY plane.

Let us assume that the main parameters of the hydraulic distributor are the same as those of standard hydraulic distributors with a nominal passage diameter of 10 mm. For example, WE10 [7]:

Nominal passage diameter – 10 mm; Maximum working pressure – 315 bar; Nominal flow rate – 100 l/min; (0.0017 m^3/s);

As a global parameter, we set the reference pressure value Pref=101000 Pa (atmospheric pressure).

The working medium is a working fluid with the following properties:

Temperature – 50oC;

Density – 850 kg/m^3;

Molar mass - 0.029 kg/mol; Viscosity - 34.85 mPa s (kg/m·s);

Thermal conductivity - 0.022 W/m·K; Specific heat capacity - 1000 J/kg·K

Since turbulent fluid motion is being modelled, a turbulence model was used together with the equations of motion. In our case, a standard k-e turbulence model (k-epsilon standard) was used.

At the inlet, the normal mass velocity W was set, corresponding to the flow rate through the hydraulic distributor:

W = mass flow rate/area = 0.142/0.000095 = 1491.2 kg/s·m^2 .

Assuming that large vortices formed in the spool zone could reach the outlet, the boundary conditions "Inlet/Outlet" with a relative pressure value of 0 Pa were assigned to the outlet section, since the flow of fluid through the distributor into the atmosphere is modelled, and the atmospheric pressure is already specified above as the reference value.

To accelerate the convergence of the solution results to a steady state, the project specifies an initial approximation in the form of the following initial condition: the velocity along the X-axis is 21.66 m/s, which corresponds to the fluid flow rate in the inlet section

To create a uniform calculation grid along all axes, an initial grid was set with the following number of cells along the axes: X: 200; Y: 60; Z: 40.

During the solution, the relative pressure and flow velocity distribution were displayed, constructed in the plane of symmetry of the hydraulic distributor. In addition to the flow velocity distribution, the figures (Fig. 5) also show the streamlines and velocity vectors.

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One of the main objectives of this simulation is to determine the average pressure at the inlet A and outlet B of the hydraulic distributor.

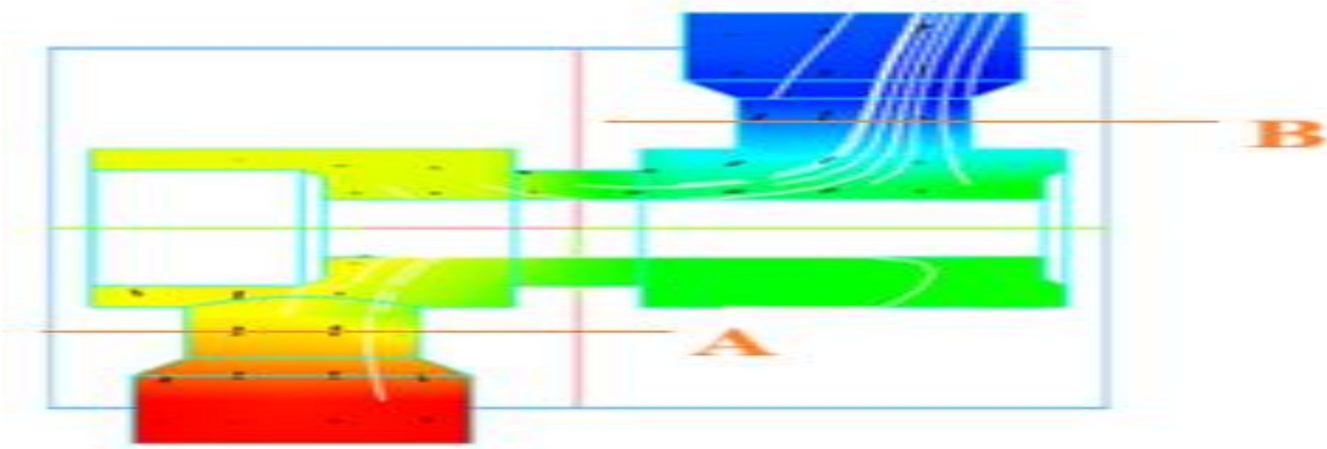

Figure 5. Flow movement through the hydraulic distributor in the plane of symmetry with colouring – pressure visualisation

In order to determine the average pressure P in these sections and monitor the dynamics of its change during the calculation, a "Result" was created in the plane of the inlet A and outlet B fittings (Fig. 6).

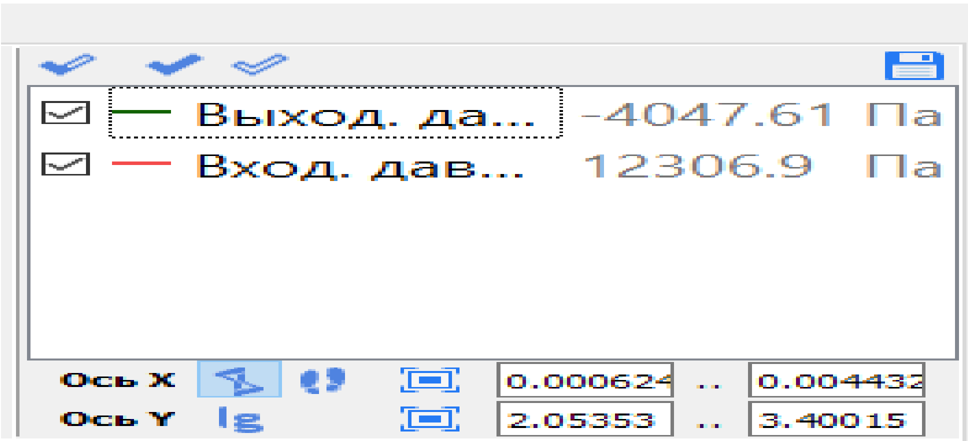

Figure 6. "Result" for the average relative pressure in the control sections at the inlet A and outlet B.

The "Discrepancy" graph (Fig. 7) allows us to judge the convergence of the entire solution. As a result of the solution, we can see that after 1 s, the discrepancy value decreases to a minimum, showing the deviation of the approximation from the exact solution.

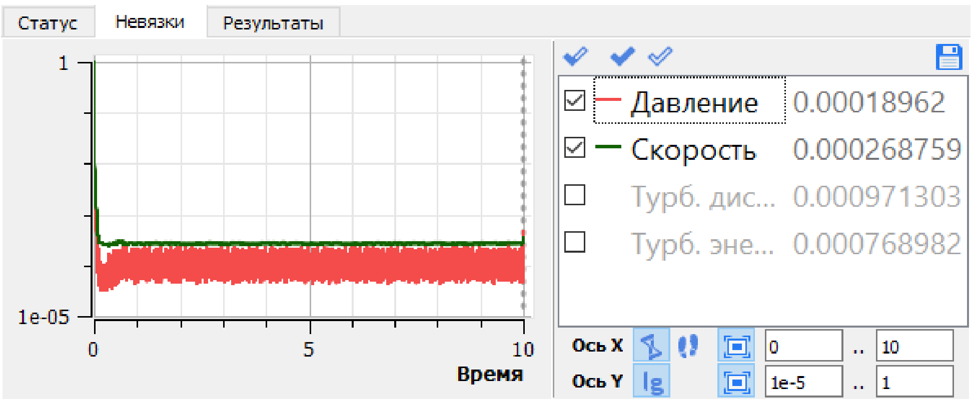

Figure 7. "Discrepancy" graph for the average pressure and velocity in the control sections

In accordance with the visualisation of the flow in the distributor, it was established that the pressure at the inlet (section A) significantly exceeds the pressure at the outlet of the distributor (section B). The average relative pressure values in these sections are shown in the "Result" tab (Fig. 6).

The total pressure loss across the hydraulic distributor $\Delta p\_$ is the difference between the absolute pressures at the inlet A and outlet B:

$\Delta p_o = \Delta pA - \Delta pB$

In turn, the absolute pressure in each section is composed of the reference pressure Pref (atmospheric pressure) and the relative pressure p:

$\Delta p_o = (Pref + pA) - (Pref + pb)$ Thus, for the conditions specified above, the pressure loss is:

$\Delta p_o = (Pref + pA) - (Pref + pb) = (101000+12306.9) - (101000 - 4047.61) = 113306.9 - 96952.39 = 16354.5$ Pa

When the flow rate is halved, the pressures at control points A and B are shown in Fig. 8.

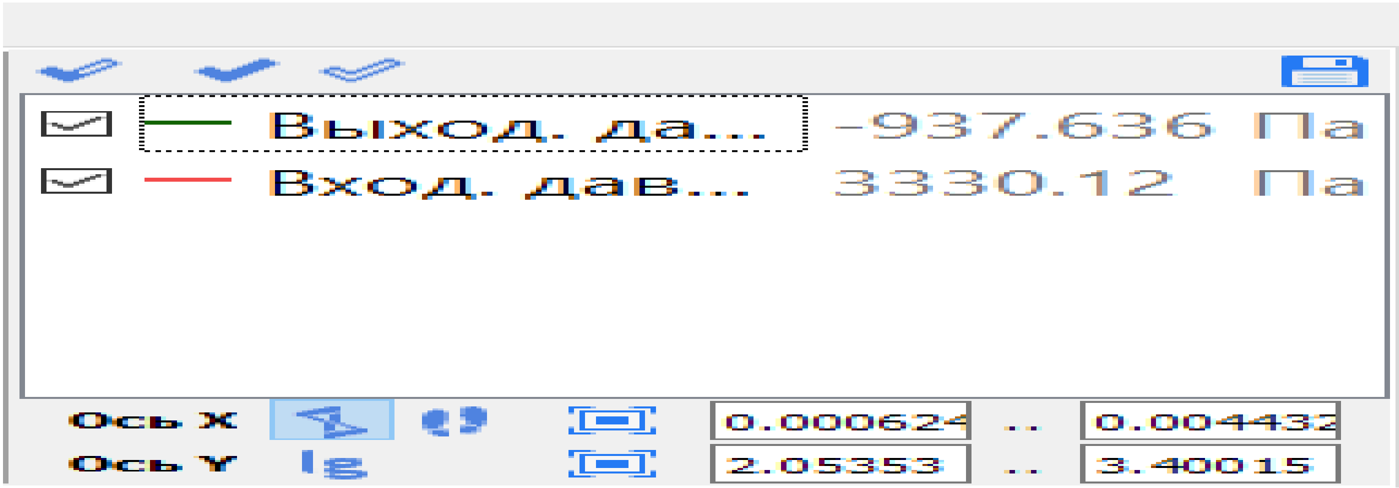

Figure 8. "Result" for the average relative pressure at control sections at inlet A and outlet B

When the flow rate is halved Pressure losses amounted to:

$\Delta po = (Pref + pA) - (Pref + pb) = (101000+3330.12)-(101000-937.636)=104330.1-100062.364=4267.736$ Pa

In our case, with a twofold reduction in flow rate, pressure losses decreased by 3.83 times.

The results of the pressure loss study, calculated in the Kompas Flow programme, are fully consistent with the pressure losses presented by PONAR Wadowice in the graphical characteristics (Fig. 2).

DISCUSSION.

The results of the rapid analysis of fluid flow through the hydraulic distributor in the KompasFlow programme clearly show how the pressure and velocity of the fluid moving in the hydraulic distributor change and how energy is lost and efficiency is reduced.

Pressure losses occur due to the formation of stagnant zones in certain parts of the hydraulic distributor, sharp changes in the direction of flow, and sudden changes in the cross-sectional area of the flow (areas of expansion and constriction). These areas are clearly visible on the visualisation layer. Fig. 8 shows the visualisation layer of the flow velocity through the distributor, with streamlines and velocity vectors. This figure shows the locations of stagnation zones and changes in flow velocity at turning sections and places of narrowing and widening.

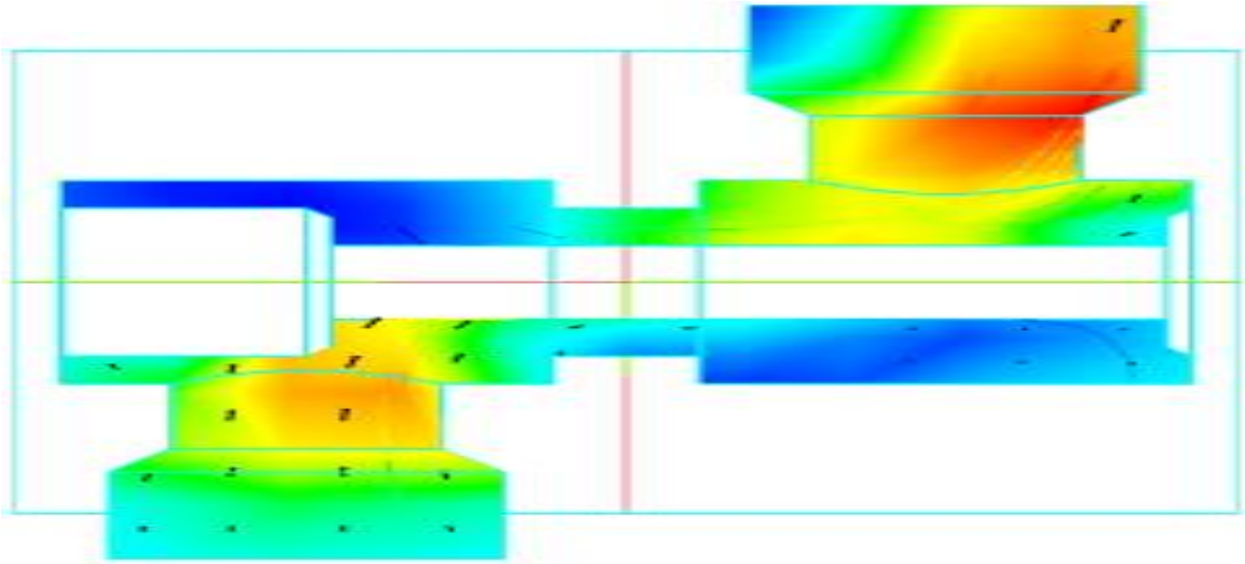

Figure 9. Flow through the hydraulic distributor in the plane of symmetry with colouring – visualisation layer of flow velocity.

It is obvious that in order to reduce pressure losses and increase efficiency, it is necessary to eliminate all of the above phenomena: stagnation zones, turns, narrowings and widenings.

However, the design and operating principle of a spool hydraulic distributor do not allow the elimination of stagnant zones, turns, constrictions and expansions of the flow.

Therefore, judging by the graphical dependence (Fig. 1), reducing energy losses in modern spool hydraulic distributors is only possible by reducing the flow rate of fluid passing through the hydraulic distributor. This position is confirmed by the calculation "Result" of the programme, Fig. 8, where a decrease in the pressure difference at the inlet and outlet is clearly visible.

However, reducing flow to lower energy losses in the distributor leads to a decrease in the speed of the actuator and specific power. This effectively negates all the advantages of the hydraulic drive.

CONCLUSIONS

The analysis showed that hydraulic distributors are a key element of the hydraulic drive of mining machines, and the energy efficiency of the entire drive largely depends on their operating parameters. It has been established that the greatest energy losses are recorded in hydraulic distributors, which is due to the design features of traditional spool valves that form stagnation zones, sharp changes in flow direction and variable channel cross-sections.

Modern designs of spool hydraulic distributors do not fully meet the requirements for increasing efficiency and reducing hydraulic losses. This necessitates the development of fundamentally new solutions that optimise the structure of the working fluid flow.

A promising direction is the creation of hydraulic distributors whose design minimizes the presence of turbulence zones, sharp turns and flow irregularities. The implementation of such approaches will increase the efficiency of hydraulic drives in mining machines, reduce energy losses, increase the overall service life of equipment and ensure their application in other industries..

ACKNOWLEDGEMENTS

This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP 23469685).

REFERENCES

1. Yakushev A. (2004). Study of the energy parameters of single-bucket hydraulic excavators. Dissertation. 179 (in Russian).
2. Kruglov V.Yu. From the expansion of electric drives to the "symbiosis" of electric and volumetric hydraulic drives. Armament. Technology. Security. Control. Materials from the VIII All-Russian Scientific and Technical Conference. Kovrov: Kovrov State Technological Academy named after V.A. Degtyarev. 2018; 281–288.
3. Buriiev B.A., Akulov D.V. Hydraulic drives: review of the current state and technical application in machines and devices. Current problems of aviation and cosmonautics. Collection of materials from the VIII International Scientific and Practical Conference dedicated to Cosmonautics Day in 3 volumes. Krasnoyarsk: Siberian State University of Science and Technology named after Academician M.F. Reshetnev. 2022; 258–260.
4. Pobegailo P.A. Single-bucket hydraulic excavators: local indicators of working equipment quality in design at the load analysis stage. Technological equipment for the mining and oil and gas industries. Collection of papers from the XIX International Scientific and Technical Conference held as part of the Ural Mining Decade. . Yekaterinburg: Ural State Mining University. 2021; 263–267.
5. Kolks G., Weber Jü. Modiciency - Efficient industrial hydraulic drives through independent metering using optimal operating modes. Conference: 10th International Fluid Power Conference (IFK). Dresden. 2016; (1): 105–120 (in English).
6. Casoli P., Scolari F., Minav T., Rundo M. Comparative Energy Analysis of a Load Sensing System and a Zonal Hydraulics for a 9-Tonne Excavator. Actuators. 2020; 9(2): 39 (in English).
7. Frosina E., Marinaro G., Senatore A., Pavanetto M. Numerical and experimental investigation for the design of a directional spool valve. Energy Procedia. 2018; 148: 274–280 (in English).
8. Zardin B., Borghi M., Cillo G., Rinaldini C., Mattarelli E. Design Of Two-Stage On/Off Cartridge Valves for Mobile Applications. Energy Procedia. 2017; 126: 1123–1130 (in English)
9. Sobolevsky A. et al. (2000). Modern hydraulic distributors and ways to improve them. Construction and Road Machines, 2 (in Russian).
10. Yakushev A. (2003). Research on energy saving systems. Construction and Road Machines, 12, 35–38 (in Russian).
11. Ranev, A. (2000). Single-bucket hydraulic excavators. Ways to save energy resources. Construction and Road Machines, 6 (in Russian).
12. Sveshnikov V.K. Individualisation – a new word in hydraulics. RITM Machine Building. 2017; (2): 38–43 (in Russian).
13. Rozhkin V., Grushetsky Yu.L. (1986). The state and prospects of development of hydraulic distributors and hydraulic control devices. Construction and Road Machines, 12. (in Russian)
14. Eresko A.S. Improvement of the hydraulic drive of lifting mechanisms of lifting and transport and construction and road machines. Speciality 05.02.13 "Machines, units and processes (by industry)": Thesis for the degree of Candidate of Technical Sciences.
15. Krasnoyarsk, 2004 (in Russian)/
16. Merk, D., Schreider, B., Toms, B. Hydraulics. Grundschritte. TP 501. (2004). Berlin Heidelberg New York, Springer- Verlag. Zweite, actualisierte Auflage, 230 (in English).
17. Grinchar N.G., Zaitseva A.A. (2016). Fundamentals of Hydraulic Drive of Machines. Part 1, 442 (in English).
18. Tochilkin V., Filatov A., Zadorozhny V., Ivanov S., Kolga A., Vagin V. (2009). Fundamentals of the Functioning of Hydraulic Systems in Metallurgical Equipment. Magnitogorsk (in Russian).
19. WE10 spool-type power distributor (2024) WK499495_WE10s12 rus.dft (hydropart.ru) (in Russian).
20. Official website of KOMPAS-3D: http://kompas.ru/Web - documentation for KompasFlow (v.20): https://flowvision.ru/webhelp/kf-v20-ru/
21. Kramsakov D., Kolga A., Stolpovskikh I., Aleksandrov V. (2024). A new approach to the design of shut-off and control pipeline valves. Bulletin of the Kurgan State Agricultural Academy, 2 (50), 53-61 (in Russian).