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Improving the efficiency of a hydraulic drive with a closed-loop hydraulic circuit

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Abstract. While developing the Arctic territories, the use of mechanical equipment, adapted to work at low temperatures, is required. The power element of hydraulic machines is a hydraulic fluid, which, under different ambient conditions, changes the viscosity-temperature properties. With decreasing temperature, the viscosity increases. The hydraulic fluid lubricity of the rubbing surfaces of the hydraulic drive elements is declining. On rubbing surfaces, the oil film strength decreases, which leads to its rupture. A hydraulic circuit of the hydraulic drive is proposed, containing an additional adjustable throttle. When throttling the working fluid, the thermal energy releases. The process of throttling the working fluid is described by differential equations. To simulate the proposed system, a dynamic closed-loop hydraulic model was compiled using MATLAB&Simulink. Modeling the hydraulic drive made it possible to obtain the time dependences of the working fluid pressure as it leaves the throttle. The obtained dependences by mathematical modeling made it possible to determine the effect of the differential pressure on the throttle on the fluid flow rate, as well as the dependence of the decrease in the liquid flow coefficient on the differential pressure. The use of a throttle hydraulic actuator with a closed-loop hydraulic circuit ensures stable temperature conditions.

1. Introduction

While developing the Northern territories, the use of mechanical equipment, adapted to work at low temperatures, is required. The power element of hydraulic machines is a hydraulic fluid. The viscosity of the working fluid depends on the outside temperature. With decreasing temperature, the viscosity of the working fluid increases, which leads to an increase in energy losses in the hydraulic drive, which causes a decrease in the technical and economic efficiency of using a hydraulic machine. The conducted studies on hydraulic machines operating at low temperatures allow one to attribute the operating mode to severe. A change in the state of the hydraulic actuator at low temperatures affects the reduction of the technical performance of the machine, in particular, the decrease in the volumetric efficiency of the pump. Studies have shown that pumps account for 40% of failures. All this leads to a loss of operability of the hydraulic drive at low temperatures. One of the ways to increase the operational reliability of hydraulic machines for machine operation at temperatures below -40°C requires additional heating of the working fluid. With the passage of the working fluid through the throttle, the pressure and speed change when it leaves the throttle [1-2]. This leads to the release of additional thermal energy. However, it is practically impossible to provide heating of the working fluid with a large volume by throttling. This effect is possible when using only a closed hydraulic drive system. Hydraulic drive studies by known methods are expensive [3, 4]. Therefore, to obtain accurate results, MATLAB&Simulink was used [5, 6]. In [7], studies on the hydraulic system of a walking machine leg using mathematical modeling and a mathematical model are presented. The issues of temperature regulating for the

hydraulic fluid of the hydraulic drive were considered in [8-11]. Purpose of this paper is to study a hydraulic drive with a closed-loop hydraulic circuit.

2. Methods and materials

The object of research is a hydraulic drive with a closed-loop hydraulic circuit (figure 1).
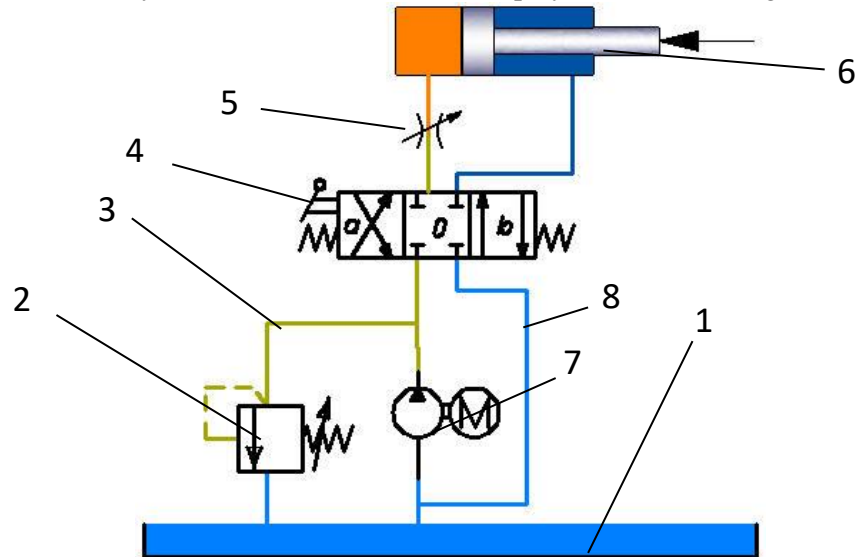
Figure 1. Hydraulic drive with a closed-loop hydraulic circuit: 1 – hydraulic fluid tank; 2 – safety valve; 3 – fluid conductor; 4 – piston valve; 5 - throttle; 6 – hydraulic actuator; 7 - pump; 8 – pump inlet line.

An additional adjustable throttle is installed in the pump line of the hydraulic actuator. The discharge side is connected directly to the inlet pipe. In this case, the working fluid circulates in a small circle, bypassing the drain into the tank of the machine. A safety valve is provided to protect the pump from overload.

3. Results

The study on the hydraulic drive with throttle control of the flow rate of the working fluid was carried out using mathematical modeling. The process of recirculation of the hydraulic fluid is described by differential equations

$$\mu_{dp} f_{dp} \sqrt{\frac{2g}{\gamma}} (P_{\partial p} - P_{\textit{вых}}) - Q_{ym.} = \frac{\pi \cdot d_T^2}{4} \cdot \frac{dx_T(t)}{dt} \tag{1}$$

$$(p_{\partial p} - p_{\textit{вых}}) = \Delta p \tag{2}$$

$$\Delta p = \frac{\xi \cdot u^2 \gamma}{2g} \tag{3}$$

$$f_{dp} = l_{\textit{щ}} \cdot b(t) \tag{4}$$

where μ_{dp}– fluid flow rate through the piston valve; f_{dp} – area of piston valve passage; Υ – liquid density; g – acceleration of gravity; $P_{др}$ –the inlet pressure of the hydraulic fluid; $P_{вых}$ – the outlet pressure of the hydraulic fluid; $Q_{yт}$ – hydraulic leak; d_T – line diameter; m_k- piston valve mass; x_k – piston valve acceleration; $c_{пр}$ – spring force; x – piston valve displacement; ΔP_{dp} – inlet and outlet pressure difference; $F_к$ – hydraulic pistol end area of the main valve; β – dissipation factor; ζ – local resistance coefficient; u – hydraulic fluid speed; $l_{ш}$ – length of the narrowest slot; b – slot width.

Equation 1 describes the balance of the flow rate of the working fluid in the piston valve and hydraulic cylinder. Equation 2 is the dependence of the differential pressure of the working fluid on the throttle. Equation 3 describes the dependence of the differential pressure on the speed of the working fluid. Equation 4 presents dependence of the slot area of the valve depending on the slot length and width.

To simulate the throttle hydraulic actuator operating procedure, the MATLAB&SIMULINK package has been taken. The model for regulating the hydraulic fluid flow in a MATLAB & Simulink is shown in figure 2.
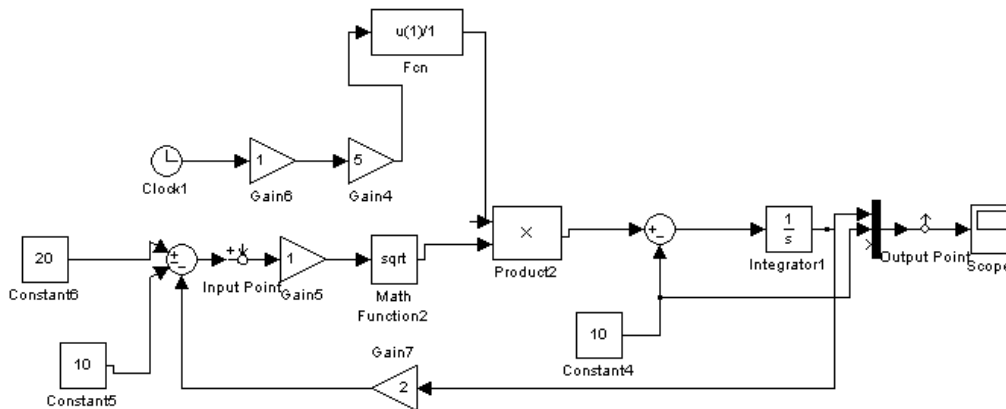

Figure 2. Hydraulic actuator fluid flow control model in MATLAB & Simulink

Boundary conditions:

f_{dp} − area of piston valve passage, 4e-6; ξ − local resistance coefficient, 0.6; μ_{dp}− fluid flow rate through the piston valve, 0.71; Υ − liquid density, 900.

Under the assumption the following have been taken: the flow rate coefficients of the working fluid are constant; fluid overflow in the hydraulic drive system is insignificant; pressure in the drain line is constant.

Based on the results of mathematical modeling, the dependences of the fluid flow rate on time in the pressure and drain lines are constructed (Figure 3.) The transition process of recirculation of the working fluid lasts 2-3 seconds. At the starting moment, turbulence in the movement of the working fluid is observed. At a critical value of the differential pressure across the throttle, cavitation occurs.
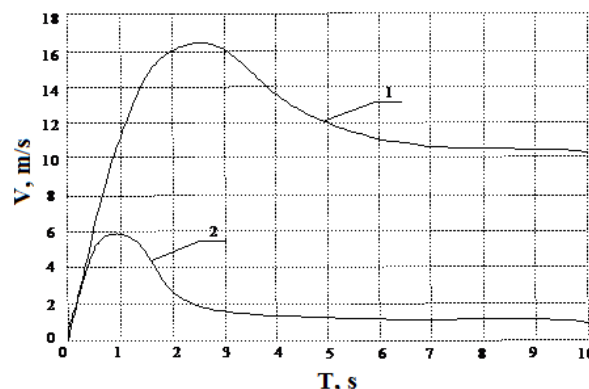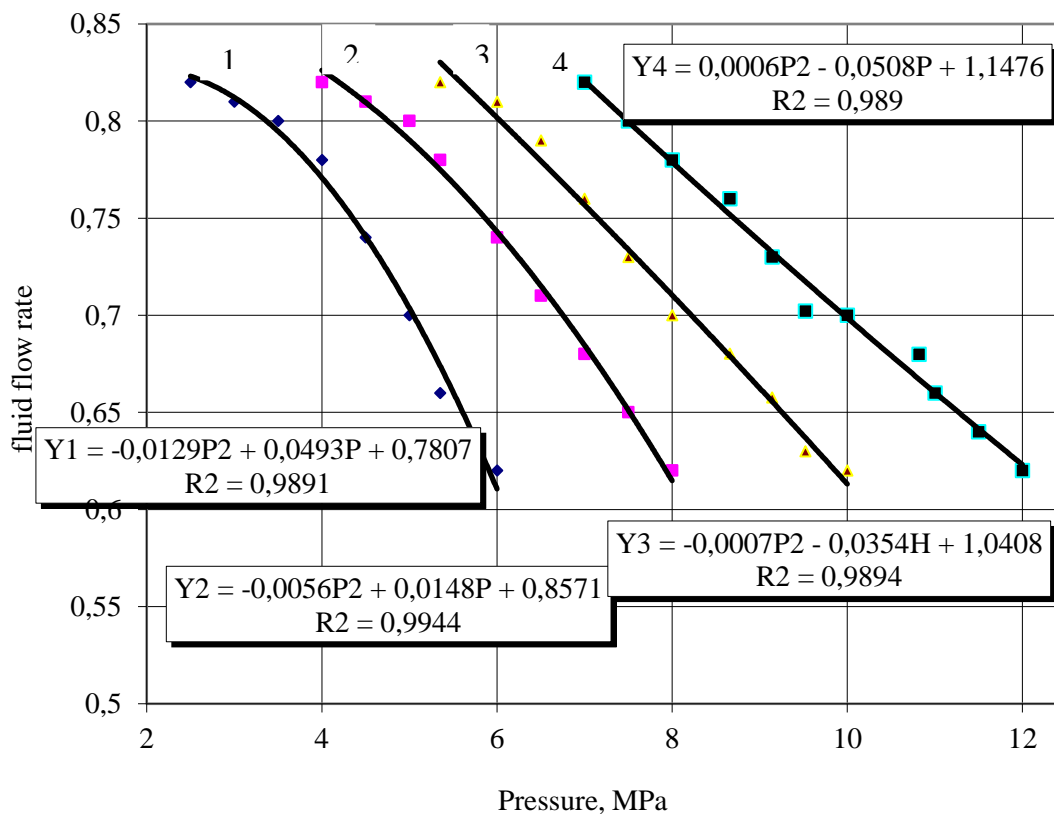

Figure 3. The dependence of the fluid flow rate in time: 1 – fluid flow rate at a pressure of 10 MPa; 2 - fluid flow rate at a pressure of 1.0 MPA.

The effect of the differential pressure across the throttle on the fluid flow rate is shown in Figure 4.
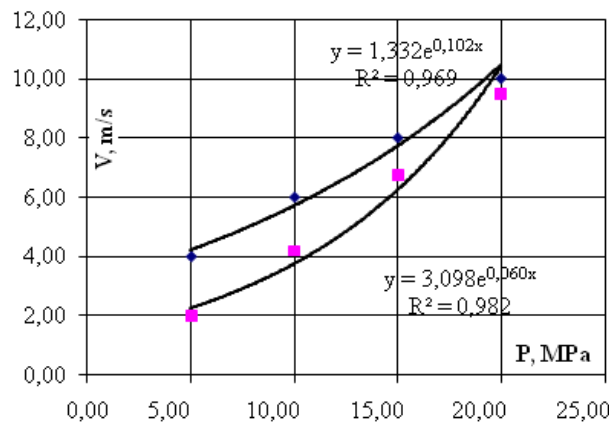
Figure 4. The effect of the differential pressure across the throttle on the fluid flow rate.

Figure 5 shows the dependences of the reduction of the liquid flow coefficient on the pressure drop: 1 - pressure 6.0 MPa; 2- pressure 8.0 MPa; 3- pressure 10.0 MPa; 4- pressure 12.0 MPa.

Figure 5. Dependences of the fluid flow coefficient reduction on the pressure drop: 1 - pressure 6.0 MPa; 2- pressure 8.0 MPa; 3- pressure 10.0 MPa; 4- pressure 12.0 MPa.

4. Discussion

As the pressure drop increases, the fluid flow rate increases from 0.61 to 0.83. The change in the flow coefficient occurs nonlinearly. A sharp increase in pressure drop leads to cavitation processes in the system. When cavitation occurs, there is a sharp decrease in the liquid flow coefficient. A decrease in the liquid flow coefficient is associated with an increase in the cavitation zone. The value of the fluid

flow coefficient is affected by the configuration of the inlet and outlet channels of the piston valve. This is due to the occurrence of hydrodynamic forces in the piston valve. A decrease in the hydrodynamic force in the piston valve is ensured by the exclusion of negative values of the hydrodynamic force. For this, the configuration of the inlet and outlet channels of the piston valve is recommended to be carried out based on the Archimedean spiral.

The simulation results of a hydraulic drive with a closed-loop hydraulic circuit are confirmed experimentally. Experimental studies were carried out in a cold chamber at a temperature of -60°C. By throttling the fluid, the suction functions of the pump can be improved and the temperature in the tank can be raised. Studies in the cold chamber were carried out at an ambient temperature of up to - 48^{0}C. It was experimentally determined that the intensity of oil heating in the hydraulic system is 2 deg/min. The thermal conductivity coefficient of the installation: maximum 70 W/m^2 deg, nominal - 40 W/m^2 deg. In the first 30 minutes of the hydraulic drive operating, the intensity of heating the hydraulic fluid was 2 deg/min. After 2 hours, the intensity of the heating of the hydraulic fluid decreased to 1 deg/min. The pressure in the pressure mains was 15 MPa, the frequency of the hydraulic pump shaft was 800 rpm.

5. Conclusions

An analysis of the thermophysical parameters of the hydraulic fluids used in the hydraulic machines made it possible to clarify the values necessary for the implementation of the thermodynamic method for calculating a hydraulic drive with a closed-loop hydraulic circuit. The introduction of an additional throttle into the hydraulic drive made it possible to ensure the required operability of the machines during operation at low temperatures. A mathematical model has been developed that allows one to analyze dynamic processes. The simulation results in MATLAB&SIMULINK determined that turbulence of the hydraulic fluid flow is observed in the starting mode. The increase in pressure drop across the throttle causes an increase in the fluid flow rate by 37.5%. A decrease in the fluid flow coefficient with increasing pressure is observed: a sharp increase in the pressure drop in the fluid flow leads to ruptures and an increase in the cavitation threshold. The flow rate of the hydraulic fluid in the inlet area reaches 16 m/s, in the outlet area up to 6 m/s. The results of mathematical modeling of a hydraulic actuator with throttle control of the hydraulic fluid supply are confirmed experimentally at an ambient temperature of -60°C.

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