Investigation and Development of the Thermal Preparation System of the Trailbuilder Machinery Hydraulic Actuator

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Abstract: It’s determined that the main part of trailbuilders operated in the North is the technology equipped by the hydraulic actuator. Further development of the northern territories will demand using of various means and ways machinery thermal preparation, and also the machinery of the northern fulfillment. On this basis problems in equipment operation are defined. One of the main is efficiency supplying of a hydraulic actuator. On the basis of the operating conditions' analysis of trailbuilder hydraulic actuator operation it is determined, that under low negative temperatures the means of thermal preparation are necessary. The existing systems warm up only a hydraulic tank or warming up of the hydro equipment before the machinery operation is carried out under loading with intensive wears. Thus, with the purpose to raise the efficiency of thermal hydraulic actuator, operated far from stationary bases autonomous, energy saving, not expensive in creation and operation systems are necessary. In accordance with the analysis of means and ways of the thermal preparation of the hydraulic actuator and the thermal balance calculations of the (internal) combustion engine the system of the hydraulic actuator heating is offered and is being investigated. It contains a local hydraulic actuator warming up and the system of internal combustion engine heat utilization. Within research operation conditions of the local hydraulic actuator heating are viewed and determined, taking into account constructive changes to the local hydraulic actuator heating. Mathematically modelling the heat technical process in the modernized hydraulic actuator is considered. As a result temperature changes of the heat-transfer and the hydraulic cylinder in time are determined. To check the theoretical researches and to define dependences on hydraulic actuator warming up, the experimental installation is made. It contains the measuring equipment, a small tank with the heat exchanger of the burnt gases of the internal combustion engine and the hydraulic cylinder with by-pass.

1. Introduction

Nowadays in the North of the Tyumen region and other northern regions of the country, a large fleet of trailbuilders is being operated. Recently, the equipment quantity used has sharply increased due to the completion of new gas fields in Yamal, large scale road construction and the laying out of new gas pipelines in Eastern Siberia. At the same time, the majority of this fleet consists of general purpose construction machinery, i.e. fleet not having the northern version [3]. It is obviously confirmed by the trailbuilder market expansion of rather cheap technique produced by South East Asia and China manufacturers. These manufacturers prefer to produce all-service equipment, shifting the problem of adaptation to local conditions onto the operating organizations.

The adaptation problems to northern conditions, thermal preparation of the internal combustion engine (ICE), hydraulic and hydromechanical transmissions of the systems of the hydraulic actuator
of the trailbuilders are topical today. At the same time, if in the matters of the thermal preparation of ICE and hydraulic transmissions there has already been some progress, the thermal preparation of hydraulic systems has been less worked out [1].

2. Methodology

2.1. Analysis of the systems of thermal preparation of the hydraulic actuator

The most popular and having practical interest for today are the schemes of working fluid warming-up in the hydraulic systems of trailbuilders (Figure 1): throttle, reducing the hydro tank volume, electrical heaters, exhaust gases of internal combustion engines and with thermal accumulators usage.

Throttle warming of the working fluid (Figure 1a) allows in 16-25 minutes to come out to optimal thermal mode, at that practically does not require the introduction of construction changes into the hydraulic system. To install the throttle 3 is possible in the forcing line between a pump 2 and a distributor 4 or on the exhaust line behind the distributor in front of the filter. The latter is preferable, because in case of the throttle full closing the hydro system is defended from overloads by a safety valve of a distributor.

Very often in practice they use throttle warming-up by passing the fluid through the safety valve when stopping the operation equipment into insuperable obstacle, that allows to preheat the working fluid intensively. However, in this case the hydraulic actuator works under pressure, which is 15…20% higher than nominal, and under low temperatures because of inertance of transferring the direct impulse peak pressure is twice as high as nominal.

Such operation mode is accompanied by the vibration of a hydro system, increased noise, leads to a premature wear, and sometimes to a destroy of hydro equipment.

The noticeable affect is given by the usage of small hydro tanks (Figure 1b) for heating the working fluid. For instance, it reduces the duration of heating the hydraulic system of scrapers by 5 times, and other machinery by 1.5…2 times. For the vehicles of northern version, especially having not heat intense hydraulic actuator, it’s reasonable to use hydro tanks of decreased capacity, because only this small constructive change allows to raise the working capacity of a vehicle by 1.5…2 times in the heating period. When designing the hydro tank of a smaller capacity it must be remembered that the height of the fluid column in it should not be lower than the minimum level excluding the formation of a funnel in a sucking nozzle.

For the machinery with a heat intense hydraulic actuator the usage of small hydro tanks is also possible, however, in summer time it is necessary to use the tank of normal volume or a special oil cooler[2].

On (Figure1b) a simplified scheme to heat the working fluid of a hydraulic actuator is shown by changing the volume of a hydro tank, where: 1 – a hydro tank; 2 – a pump; 3 – a distributor; 4 – a small hydro tank, 5 – a switch.

Using the electric heating of the working fluid (Figure 1c) by heating elements, placed in the hydro tank is possible only if the self-moving machinery is equipped with the generator of the capacity not less than 30-40 % of the nominal pump arrangement capacity or feeding the machinery from the electrical-nets. In this case, as the estimates and the experience of foreign firms show it is possible to heat the working fluid from –40°C to the optimal temperature for 15-20 minutes. Electrical heating of oil unlike other ways allows to perform local heating of hydro equipment, rather far away from a hydro tank and internal combustion engine. To exclude the local oil overheating and its chemical decomposition simultaneously with switching the electrical heaters on, a hydro pump must be switched on too, providing the continuous circulation of fluid in the hydraulic system. On (Figure 1c) the simplified scheme of the way to heat the working fluid with the help of electrical heaters is shown: where 1-a distributor; 2 – a pump; 3 – a hydro tank; 4 – an electric heating element.
Figure 1: Schemes of working fluid warming-up: a) throttle, b) changing the hydro tank volume, c) electrical heating, d) using the heat of the exhaust gases

The biggest effect when heating the working fluid is reached by using the exhaust gases of ICE (Figure 1d), at that the duration of heating the working fluid is only 13-15 minutes, that is confirmed by experimental investigations. However, the complexity of the given way is in the fact that it is necessary to make significant changes in the construction of a hydro tank, making the technology of its production more complex and complicating the service in the process of operation [4]. But nevertheless this way found a wide implementation on earth-moving, load-lifting and other machines. On (Figure 1d) a simplified scheme to heat the working fluid with using the exhaust gases of ICE is shown: 1 – ICE; 2 – an exhaust tube; 3 – a hydro tank, 4 – a pump.

It should be noted, that the duration of hydraulic system transferring to the optimal thermal mode depends on the construction of hydraulic actuator as well as on the mode of machine operation, determined by its purpose. Thus, for example, at initial temperature of the working fluid of minus 40°C, it reaches the minimum value of optimal temperature of the working fluid of 0°C without using the devices for heating in a hydraulic system within 85 minutes, bulldozer-ripper after 125 minutes, and a scraper only after 5 hours of the excavator continuous work. That's why the choice of the way to heat the working fluid must take into account climatic operation conditions, and also type, design and technical level of the machine. For example, to raise the workability of hydraulic actuators during winter time in the southern regions and the regions of the middle part of the country, the usage of the tank of lower capacity may be enough, for the regions with cold climate it is also reasonable to use a smaller hydro tank but in connection with throttle or other kind of heating[7].

2.2. Description of the suggested system of thermal preparation of a machinery hydraulic actuator

The existing means of hydraulic actuator thermal preparation are power consuming, require much time, do not support its optimal thermal mode and local heating of the elements of the hydraulic actuator. Since the systems of thermal hydraulic actuator preparation that had been suggested before, implement the heating of oil, which is in the hydro tank and hydro line and moves in the small circle. At that hydro engines remain unheated and with multiple-viscosity oil in it significantly makes the beginning of movable elements activity harder in the places of compression.

It is necessary to reduce the load degree at the moment of first starting the hydro engine, which will allow reducing the wear intensity and prolonging the service duration of the hydraulic actuator elements [4]. It is also necessary to use the heat of internal combustion engine exhaust gases (heat utilization).

The necessity appears to optimize the hydro tank and layout of pipelines, and also heating the hydraulic actuator with local influence on its elements [5]. The existing schemes of heating the hydro
systems do not provide autonomy of operation, have high energy intensity and labor intensity of service, limitation in implementing different arrangements of the hydraulic actuator – these lead to the decrease of ergonomic indexes of trailbuilders.

Estimates of thermal balance of the internal combustion engine showed that nearly 25% of the thermal energy during engine operation comes out with exhaust gases (Figure 2).

In accordance with the analysis of thermal preparation means and the estimation of the thermal balance, the system of thermal preparation of the machinery hydraulic actuator is being developed. In the suggested design to reduce the time of thermal preparation a small hydro tank and local heating of the hydro cylinder are included additionally into the standard hydro system of the hydraulic actuator of trailbuilder machinery.

This system is based on the use of the thermal energy of the exhaust gases of the trailbuilder ICE. For this purpose, a gas switch is installed on the engine exhaust manifold which allows changing the exhaust gases stream into two directions: in the muffler (during the work) or via the gas pipeline, in the heat exchanger built in the hydro tank (while power fluid heating)[6, 8].

Connection of the gas pipeline with the heat exchanger is executed by means of the bellow valve which allows removal of the vibration loadings caused by the raised level of vibration of the trailbuilder ICE.

The heat exchanger is located in the lower part of the hydro tank so as to allow a reduction in the power fluid heating throughout the hydro tank, due to the increased convection of the power fluid; moreover, the heat exchanger placement below the level of the power fluid prevents it burning even in the case when the temperature of the wall of the heater is much higher than the boiling point of the power fluid.

![Figure 2: Thermal balance of the internal combustion engine. EG – exhaust gases CL – energy of cooling liquid. Friction, Useful energy](image)

A key condition of modernization was the requirement for preservation of the commercial hydraulic system, including design of the hydro tank and the facilities for its attachment. It is necessary for the pump to be below the tank by not less than 50 cm and to provide delivery of warm power fluid to the pump from the hydro tank [10].

Calculations show that the time for a power fluid to heat from –40 °C to 0°C doesn't exceed 25 minutes; however, the heating time can be reduced if there is increased turbulence of the gas stream in the heat exchanger.

A small hydro tank is built between the main hydro tank and a hydro system pump. This allows before starting the hydraulic actuator to heat a small amount of the working fluid. At that the hydro tank is set lower than the main hydro tank and is connected with it by the tube of big section for the working fluid to come to a small hydro tank spontaneously. Also possible is the variant when a small tank is located in an optional place of the arrangement and is connected with the main tank by the tube of big section, additional pump for the viscous working fluid (tabular or spiral construction) and globe valve with valve control to doze the working fluid coming into a small hydro tank.

A pump serves to pump over the viscous working fluid into a small hydro tank. As opposed to the main pump (a hydro pump) it works at low pressure dozing the coming of the working fluid into a small hydro tank. In the construction the circulating pump is also provided for throwing a part of heated working fluid into the main tank to avoid the overheating of the working fluid. The block of
automatic control serves to control the pneumatic valves and pumps, it collects the information from
the temperature and fluid level sensors, located in the main hydro tank as well as in a small one for the
automatics to throw out the excess of the heated fluid from the small hydro tank into the main one, and
also to add new fluid into the small tank.

When the heating of the working fluid is not required, a valve, which is located in the exhaust
system is closed. And with the help of three-way cock they transfer the hydro system onto normal
mode of the main tank operation.

The local heating is authorized for the hydro equipment, located on the periphery of the
machine. The hydro cylinder with the additional hydro line is being investigated [9]. By the branches
stocked and rodless chambers of the hydro cylinder are connected with the additional hydro line
through the valve or electromagnetic valve. The valve serves to combine the hydro cylinder chambers
when heating and their division at normal hydro cylinder operation. The heating of the hydro cylinder
is realized in the following way: movement of the heated in the hydro tank working fluid from one
chamber into another by the additional hydro line, connecting stocked and rodless chambers of the
hydro cylinder which provides the thermal change with a body, a stock, a piston of the hydro cylinder.

The open valve of the additional hydro line allows the heated working fluid to flow free in the
chambers of the hydro cylinder. After finishing the cycle of hydro cylinder heating, the valve is closed
thus stopping the movement of the working fluid through the bypass pipeline. When the valve is
closed the working fluid acts on the piston, moving it in the body of the hydro cylinder. This gives the
working mode to the hydro cylinder.

This allows heating the working fluid significantly quicker, than to heat the whole hydro tank of
the machine, thus, reducing the time of heating preparation of the machine. The heated working fluid
moves through the hydro pump, hydro equipment, pipelines, in this way the whole hydro system is
heated, at that the system of heating hydro engines is provided by using the additional distribution of
pipelines, at which the beginning of the working fluid movement is realized without stock movement
(high wears in the beginning of operation are reduced).

2.3. Mathematical modelling process of the thermal preparation hydraulic actuator

To work out the given system it is necessary to carry out calculations, explorings, describing
heat technological processes in a modernized hydraulic actuator.

For the by-pass hydraulic cylinder, according with one of the main laws of the fluid and gas
mechanics – with the help of the equation of the thermal balance, of the motive medium (heat-transfer
agent): time - total derivative from inner energy, given off mass of the motive medium is equaled to
the sum of the heat power supplied or derived from heat-transfer agent and power of the inner viscous
forces. One can usually disregard by heat flow in consequence of the heat conductivity of the heat-
transfer agent along the normal in the entrance and outlet sections from the system of the heat
preparation hydro cylinder. Heat power, transferred from heat-transfer agent (temperature \(T_a\)) to hydro
cylinder (convective heat abstraction area \(F_a\), temperature \(T_c\)) is defined by the convective heat
abstraction equation \(Q_{ac} = \alpha_a F_a (T_a - T_c)\) [11].

Nonstationary processes in a heat-transfer agent system of the thermal preparation and in a
hydro cylinder approximately are described by two differential equations for averaged temperatures of
the heat-transfer agent \(T_a\) and hydro cylinder \(T_c\), and also by the equation of the heat-transfer agent
charges’ balance in sections \(S_1\), \(S', S'', S_2\):

\[
\begin{align*}
c_m & \frac{\Delta T_c}{\Delta t} = G_1 c_s T_1 - c_s c_T^2 - G' c_s T^* + G'' c_s T'' - Q_{ac} \\
c_m & \frac{\Delta T_a}{\Delta t} = Q_a - Q_s \\
G_2 & = G_1 - G' + G''
\end{align*}
\]
In the first place, the more the hydraulic reservoir tank, the more heat quantity it is necessary to use to the cylinder will lose some amount of heat, under heating – absorb. Heat quantity is up on the next values.

On the warming-up stage of hydraulic duration 5-10 minutes in the temperature range of the surrounding air from –40 °C till –15 °C. At the hydro system with temperature of the working fluid under heating (40 °C) and after heating (+50 °C) explorings using empirical model and to compare derived results with the control data [10].

Pressure in a system has to satisfy condition:

\[ \Delta P = \Delta P_L + \Delta P_M + \Delta P_H \]  

(4)

Pressure in a system has to satisfy condition:

\[ P_{nom} \leq P_{nom} + \Delta P \leq P_{max} \]  

(5)

where \( P_{nom} \) – is a nominal pumping pressure, MPa; \( P_{max} \) – is a maximum pumping pressure, MPa

If the condition is met, so offered modernization doesn’t influence on the normal work of the hydraulic system. To corroborate theoretical explorings it is necessary to carry out experimental explorings using empirical model and to compare derived results with the control data [10].

Theoretical explorings showed, that reactions in the hydraulic cylinders and pressure losses in a hydro system with temperature of the working fluid under heating (40 °C) and after heating (+50 °C) provide piston immobility under warming up of the by-pass hydraulic cylinder.

Timing warming up of the hydraulic cylinder with the help of the working fluid showed duration 5-10 minutes in the temperature range of the surrounding air from –40 °C till –15 °C. At the same time it is defined temperature lowering in a hydraulic tank on the warming-up stage of hydraulic cylinder.

It is necessary to define the heat quantity which is useful for a small hydraulic reservoir. Heat quantity is an energy, which body loses and gets by the heat transfer. Being getting cold the hydraulic cylinder will lose some amount of heat, under heating – absorb. Heat quantity is up on the next values. In the first place, the more the hydraulic reservoir tank, the more heat quantity it is necessary to use to
change its temperature on one degree. In the second place, heat quantity which is useful for the hydraulic tank warming up is up on the heat capacity of the working fluid. Thirdly, temperatures’ difference of the working fluid before and after heat-transmission influences on the total heat amount which is useful to warm up hydraulic reservoir:

\[ Q = c \cdot m \cdot (t_2 - t_1) \]

where \( Q \) – is a heat quantity (J), \( m \) – is a mass of the working fluid of the hydro reservoir (kg), \( c \) – specific heat of the working fluid (J/kg °C), \( (t_2 - t_1) \) – is a difference between initial and final temperatures of the working fluid (°C).

This formula helps to make heat quantity calculations, which is useful to warm up the hydro tank or how much heat hydro tank gives off by cooling.

Figure 3 presents results of calculations for small hydro tank (volume 10 liters)

3. Experimental investigations

The aim of experimental investigations concludes theoretical researches and dependences' definition to warm up hydraulic drive.

Principle diagram which is worked out for hydro system of the experimental installation is shown in Figure 4.

Hydro cylinders (1 and 2) are managed by the separate distributors (7). Characteristics’ measurements of working fluid are carried out inlet and outlet hydraulic cylinder, and also hydro tank.

It’s important to fix such parameters as temperature and pressure in hydraulic cylinders. It allows getting the more clear performance about processes’ characteristics. Thereupon there was set a distributing connecting pipe with measuring equipment in every hydraulic cylinder, in a pressure opening.
Figure 4: Hydraulic scheme of the experimental installation: 1 – internal-combustion engine, 2 – tank, 3 – a small hydro tank, 4 – pump, 5 – modernized hydraulic cylinder; 6 – control hydraulic cylinder; 7 – hydraulic control valve, 8 – throttle, 9 – manometer, 10 – temperature sensor, 11 – by-pass valve, 12 – filter, 13 – valve

Figure 5 shows a laboratory pattern of the by-pass hydraulic cylinder. To accelerate the working fluid warming up in the hydro tank, there was worked out a construction to use a small hydro tank (Figure 6). Such construction allows considerably to decrease working fluid time-warming up, it’s very important for technics, which is working by low negative temperatures.

By warming up of hydraulic cylinder with by-pass pipeline, the analysis of warming up diagrams showed: the wall warming up of the experimental cylinder is carried out quicker having –20°C and –40°C accordingly (10.5 and 19 minutes), than in case of control hydraulic cylinder (12.5 minutes and 24 minutes), warming up character – at the beginning of the warming up we can see the acceleration, later stable, smooth. The warming up of the control hydraulic cylinder is carried out evenly [11].

To investigate hydro tank warming up, which uses the heat of the used gases of the internal-combustion engine, there was set a heat-exchanger in the lower part of a small hydro tank. Through
this heat-exchanger was run a hot stream of used gases, warming up working fluid of a small hydro tank (Figure 6).

In the connective pipe of the modernized hydraulic cylinder temperature of the working fluid is growing quickly, and tries to reach temperature of working liquid in the hydraulic tank. On this reason there was a circulation of working fluid on the additional hydro line. Temperature rises till 0°C for 0.75 minutes. In the connective pipe of the control hydraulic cylinder temperature of working fluid rises more slowly, than modernized hydraulic cylinder, but more stable. Temperature rises till 0°C for 3 minutes (Figure 7, Figure 8).

Figure 7: Diagram of control hydraulic cylinder warming up $t_{w,0} = -40 \, ^\circ C$:
1 – hydro tank, 2 – connective pipe, 3 – hydro cylinder

Figure 8: Diagram of the modernized hydro cylinder warming up $t_{w,0} = -40 \, ^\circ C$:
1 – hydro tank, 2 – connective pipe, 3 – hydro cylinder

During experiments readings were taken from measuring instruments, processing of measurements’ results is given in the diagram of a small hydro tank (Figure 9) (by $t_{w,c} = -28 \, ^\circ C$).
Figure 9: Diagram of the warming of the small hydro tank. Sensors are set in a hydro tank: 1 – inlet heat-exchanger, 2 – middle heat-exchanger, 3 – outlet heat-exchanger, 4 – middle-volume hydro tank

The diagram shows that the highest temperature is inlet heat-exchanger in the hydro tank. The lowest temperature of the working fluid - is in the middle-volume hydro tank. At the same way temperature growth dynamics of the working fluid in the hydro tank also differs. The most intensive warming up is inlet-hydro tank, and uniform warming up is in the middle-volume hydro tank.

Conclusion

The majority of the hydraulic systems’ break-downs of trailbuilders, operated in the North are connected with an influence of low negative temperatures. Therefore there is a need to apply machines of the northern fulfillment, working fluids to use during the winter period and means of pre-starting thermal preparation of a hydraulic actuator.

The analysis of the earlier offered systems of a hydraulic actuator thermal preparation showed the following shortcomings: throttling – big resistance, low coefficient of efficiency, a warming up by burnt gases of the internal combustion engine and energy warming up – construction complexity and the construction changing of a regular hydro tank. All systems warm up only the main hydro tank. A large amount of energy and time during the start of a hydraulic actuator in work is spent for it. Thus, local warming up of the hydro equipment (hydraulic cylinders) elements at the beginning of work of the machine hydraulic actuator isn’t carried out. It conducts to intensive wears, especially at the time of the beginning of work and to decreasing in term of equipment operation.

In the offered construction, to decrease the thermal preparation time and means for the modernization of the existing technology (without changing a regular hydro system), a small hydro tank and local hydraulic cylinder warming up are included extra in a regular hydro system of the trailbuilders. It allows heating the working fluid significantly quicker, than to heat the whole hydro tank of the machine. The heated working fluid moves through the hydro pump, hydro equipment, and pipelines. In this way the whole hydro system is heated. At the same time the system of heating hydro engine is provided by using the additional distribution of pipelines, at which the beginning of the working fluid movement is realized without stock movement.

The system of equations is solved by the standard methods, for example, by Runge-Kutta method. This result is the aim of studying thermal preparation hydraulic cylinder to start. Determination of the heat amount, which is necessary to warm up a hydro tank depends on the hydro tank mass, thermal capacity of the working fluid, temperatures’ difference of the working fluid before and after a heat-transfer.

Means of the warming up of the working fluid should be chosen taking into account climatic conditions of operation, type and construction of the trailbuilder hydraulic actuator, technical production rate. For example, to increase the working capacity of the hydraulic actuator during the winter period in the southern areas and regions of a midland of the country there can be enough the...
application of a smaller capacity tank, with frigid climate it is also expedient to apply the smaller hydro tank, but in combination with the heat exchanger of the burnt gases or other means of a warming up.

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