Modeling the warm-up process for hydraulic actuator components

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Abstract. This paper discusses warm-up processes for the hydraulic system components of road construction machinery using mathematical and physical simulations. The efficiency of these processes is governed by warm-up and cool-down rates of the hydraulic actuator components. It studies how various hydraulic system components interface as they warm up. The general task is to estimate the dynamic behavior of the components and loops comprising such components and the entire warm-up system. The models of the transient heat flow process of the warm-up system are based on the heat balance equation of the flowing medium (of the heat transfer fluid – a hydraulic fluid) within the control volume. For experimental verification, the hydraulic actuator components warm-up modes using the warmed-up hydraulic fluid from the hydraulic tank have been tested on the hydraulic test bench that we developed. The example of consecutive warm-up of the hydraulic system components is given. Based on this, after the experimental findings were processed, correlation coefficients for different warm-up modes and types of relationships between the hydraulic actuator component temperatures and their warm-up times were determined.

1. Introduction
Most of the construction machinery used for building and operating facilities in northern regions of Russia is hydraulically driven; besides, these machines operate as part of packages or systems. This enhances work productivity and ensures a high level of work organization. Meanwhile, if any one of the machines breaks down, it interrupts the entire construction and repair process onsite, causing other machines either to be downtime or operate less efficiently [1]. The problem of how to warm up internal combustion engines of hydraulically-actuated machines operating in the northern climate has mostly been solved, yet, the problem of how to warm up hydraulic actuators is still open. Different warm-up systems exist for warming up internal combustion engines. There are much fewer such systems for warming up hydraulic actuators. Construction machinery operators have to spend 30 to 90 minutes to warm up hydraulic actuators before starting the work. The hydraulic actuators are warmed up by way of no-load operation (‘idle running’).

Therefore, studying the heat exchange process in hydraulic actuators of construction machinery is of great relevance.

Warming up the hydraulic actuator components is necessary for stable and failure-free operation of hydraulically-actuated machinery. Reducing the hydraulic system warm-up time increases the machine operation time and operational availability.
2. Theoretical Rationale and Mathematical Description

The study assumes that the hydraulic fluid in the hydraulic tank is warmed up. Running through the hydraulic actuator components, the hydraulic fluid emits heat to the hydraulic actuator components.

Mathematical modeling of processes in the hydraulic actuator component warm-up system is based on the mathematical models of warm-up processes of its individual components: directional control valves, valves, a hydraulic tank with a heat exchanger.

The objective is to estimate the dynamic behavior of the components, loops comprising those components, and the entire warm-up system. For this purpose, it is necessary to make assumptions that can simplify mathematical modeling of the warm-up system for the hydraulic actuator components.

The models of the transient heat flow process of the warm-up system are based on the heat balance equation of the flowing medium (of the heat transfer fluid – a hydraulic fluid) within the control volume $V$ [2]:

$$c_a m_a \frac{dT_a}{dt} = -Q_g + N_w,$$

where $c_a m_a \frac{dT_a}{dt}$ is the rate of internal energy accumulation or degradation; $G_1 c_a T_1 + G_2 c_a T_2 + G' c_a T' - G'' c_a T''$ is the heat transfer fluid internal energy flow through the control volume surface, $Q_g$ is the heat power supplied to $(Q_g < 0)$ or carried away $(Q_g > 0)$ from the heat transfer fluid to the hydraulic actuator component, $N_w$ is the internal viscous forcepower, which can be neglected when designing the warm-up system [2].

The heat balance equation for a transient warm-up process of the hydraulic actuator component is written as follows:

$$c_a m_a \frac{dT_a}{dt} = Q_g - Q_b,$$

where $Q_g$ is the heat power supplied to the hydraulic actuator component while warming up, kW; $Q_b$ is the heat power transmitted from the hydraulic actuator component to the environment, kW; $c_g$ is the heat absorption capacity of the hydraulic actuator component, $J/\degree C$; $m_g$ is the hydraulic actuator component weight, kg.

The heat powers $Q_g$ and $Q_b$ are determined using the heat transfer equations:

$$Q_g = A_g (T_a - T_g),$$
$$Q_b = A_b (T_g - T_b),$$

where the heat transfer parameters $A_g = \alpha_a F_a$ and $A_b = \alpha_b F_b$ are derived from the consolidated experimental data.

3. Preparing for the Warm-Up Study with Regard to the Temperature of a Hydraulic Actuator Components

In order to conduct experiments, a hydraulic test bench was engineered and manufactured. The hydraulic loop of the experimental test bench is shown in Figure 1.
Figure 1. The experimental test bench hydraulic system schematic: 1 - directional control valve, 2 - directional control valve temperature sensor, 3 - hydraulic valve, 4 - hydraulic valve temperature sensor.

The following components of the hydraulic actuator were used: a hydraulic tank, a hydraulic pump, pipelines, a directional control valve, a hydraulic valve. The G 54-32 hydraulic valve and the VMMB 44 F directional control valve specifications are given in Table 1 [3].

The temperature sensors were positioned on the hydraulic valve body and on the directional control valve body. The sensors were positioned closer to the channel through which the hydraulic fluid flowed out of the hydraulic system component. This allowed evaluating the heat transfer from the hydraulic fluid to the hydraulic actuator component. The hydraulic fluid temperature in the hydraulic tank before the experiment started was 22°С above zero.

The directional control valve has three positions. The two end positions connect the pressure line with Line A or B, the central position shuts off the pressure line.

After the hydraulic system was started, it was determined on the hydraulic test bench that the temperature of the hydraulic actuator components (of the valve and of the directional control valve) was rapidly going up. The temperature in the hydraulic actuator while warming up changed differently between various components. As they cooled down, the irregularity in temperature changes was also found. The non-linear relationships were observed between the discussed processes. The main parameters of the VMMB 44 F directional control valve and those of the G54-32(M) hydraulic valve are shown in Table 1.

Table 1. Main parameters of the VMMB 44 F directional control valve and of the G54-32(M) hydraulic valve.

| Parameters                                   | Value         |
|----------------------------------------------|---------------|
| Name                                         | VMMB 44 F     | G54-32(M)    |
| Directional control reference tables         | 44            | -            |
| Nominal bore, mm                             | 10            | 10           |
| Hydraulic fluid rate, l/min                  | 25-40         | 32           |
| Hydraulic control pressure minimum (maximum), MPa (kgf/cm²) | 0.8-6.0 (8-60) | -           |
| Pressure setting range, MPa                  | -             | 0.4-2.8      |
| Weight, max, kg                              | 6.45          | 2.4          |
4. Experiment
During the measurements, the test bench was used in the five following modes:

One – between 0 and 11 minutes, the hydraulic valve passes the hydraulic fluid through, the directional control valve is in the farthest position. The hydraulic fluid passes through the directional control valve.

The hydraulic actuator components are rapidly warming up, it can be seen that the warm-up is irregular. If the hydraulic actuator component is less heavy, the warm-up rate goes up. The correlation coefficient is 0.97.

Two – between 11 and 22 minutes, the directional control valve is in the central position. The hydraulic fluid does not pass through the directional control valve. This causes the warmed-up hydraulic valve to keep warming up. The correlation coefficient is minus 0.87.

Three – between 21 and 24 minutes, the mode is the same as between 0 and 11 minutes. The difference is that the warm-up takes place at different initial temperatures. The directional control valve warms up faster, even though it is heavy. The temperature of the hydraulic valve, which is lighter, does not change. The parameters correlate very little. The correlation coefficient is 0.44.

Four – between 24 and 27 minutes, there is no wind load on the hydraulic test bench. The temperature is rapidly growing. The heavy directional control valve with the lower initial temperature warms up at the same rate as the hydraulic valve that has the highest temperature at the beginning of Minute 24. The correlation coefficient is 0.98.

Five – starting from Minute 27, the hydraulic test bench shuts down. It cools down. The lighter and hotter hydraulic valve cools down faster. Meanwhile, the heavier directional control valve cools down more slowly. The correlation coefficient is 0.89.

The crossplot of the temperatures of the hydraulic actuator components versus their warm-up times is shown in Figure 2.

![Figure 2](image_url)

**Figure 2.** Hydraulic actuator components temperatures versus their warm-up times

The correlation of the hydraulic actuator components warm-up in different modes is shown in Table 2.

The relationship between these values is non-linear and can be modeled as an exponential or polynomial relationship (Figure 2). The R-squared value $R^2$ is 0.88 - 0.95. The correlation values
indicate that there is a close relationship between the output parameter of the hydraulic actuator component temperature and the factor of influence, which is the warm-up time [3].

**Table 2. Hydraulic actuator component warm-up temperature correlations**

| Mode | Duration (min) | Temperature variation | Correlation |
|------|----------------|-----------------------|-------------|
| 1    | 11             | Warm-up               | + 0.97      |
| 2    | 11             | Cool-down             | - 0.87      |
| 3    | 4              | Warm-up               | + 0.44      |
| 4    | 3              | Warm-up               | + 0.98      |
| 5    | 9              | Cool-down             | + 0.89      |

5. Conclusion
The experiments demonstrated that various components of the hydraulic system require different time periods to warm up to a certain temperature. Their warm-up times are contingent on such factors, as the initial temperature of the components being warmed up (at the initial time point, it is equal to the ambient temperature) and their weights; the temperature of the hydraulic fluid (the heat transfer fluid); the rate of the hydraulic fluid, supplied to the component being warmed up; the hydraulic fluid flow direction; the number of the hydraulic actuator components being warmed up at the same time. In order to enhance the warm-up efficiency for the hydraulic actuator components, these factors must be taken into account. Meanwhile, the objective of the study is to consider each factor (its effect), both individually and as two-factor interface. This interface process corresponds to a non-linear relationship. The experimental findings confirmed that the dynamic behavior of the components, loops comprising such components, and the entire warm-up system exists.

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