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Hydraulic Oil Temperature in Bridge Circuit and Hydraulic Bent Axis Piston as Load

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Abstract.

The aim of this research is to study the behavior of and controlling hydraulic oil temperature in bridge circuit with through path bent axis piston motor as load in the test bench. The testing of hydraulic motor efficiency was conducted in accordance with the test circuit for motor unit of ISO 4409. Measurement of inlet flow rate, drainage flow rate, output torque and test fluid temperature were all taken at full rotational speed range of the motor. The load of this circuit used for testing is the hydraulic bent axis motor 160 cc/rev connected with torque sensor 0-10 kNm. The testing of the hydraulic motor started when the load was driven and the piston moved hydraulic oil to flow and pass through the bridge circuit. The valves were checked and circulated into circuit by the proportional pressure control valve. The result showed that a high hydraulic oil flow rate of 160 l/min and high pressure of 150 bar rapidly increased the temperature up to 80 degrees Celsius. The hydraulic oil circulated in this circuit was later separated from the box valve and put into an oil cooler to reduce the temperature. Increasing the oil temperature depends significantly on the variability of the rate of oil flow and pressure. The fan at the cooler driven by a high-speed low torque hydraulic motor was controlled by a proportional relief valve and decentralized controller. The temperature of the hydraulic oil during test should be 33- 60 degrees Celsius while the speed of the hydraulic motor is regulated by input signal from sensor sent to the controller. It was found that the hydraulic bent axis motor can be used to function as load for hydraulic motor testing because the cooling efficiency of the oil greatly regulates the temperature, reduces the degree of the hydraulic bent axis motor wearing and instead increases the lifespan of the oil.

Keywords. Hydraulic oil temperature, bridge circuit, heating generation, charge system, flushing, cooling.

1.INTRODUCTION

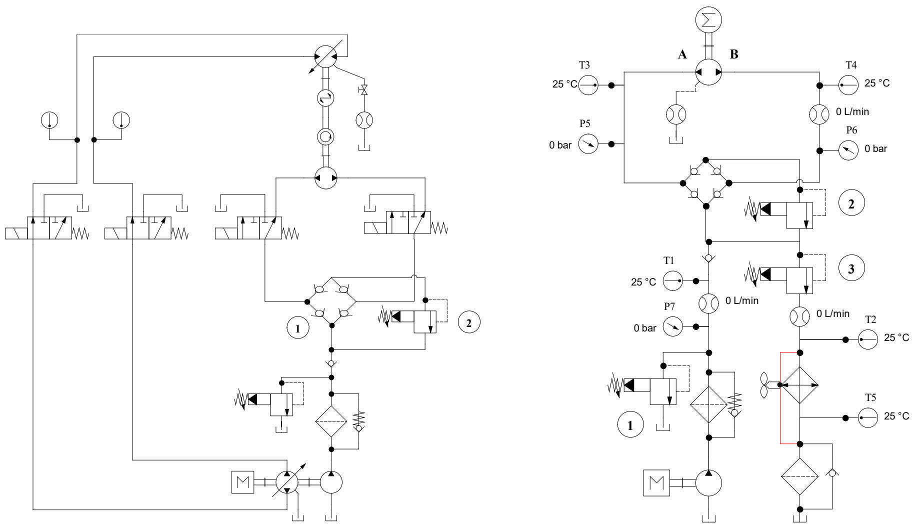
Hydraulic motor has been widely used for driving agriculture machinery including rice harvester sugar cane harvester and construction machinery. The transmission of these machinery is purely hydrostatic consisting of an open and close circuit. The repaired hydraulic motor should have high efficiency before being used. The test rig machine built up from outsource can be operated for efficiency evaluating both hydraulic motor and hydraulic pump using the same driving power and reservoir. With regards to hydraulic pump testing, the system is driven by a close-loop three phase electric motor of 75 kW and an electric displacement control (EDC) close-loop pump of 75 cc/rev. The power drive of this machine can be used in testing hydraulic motor too Figure 1. The size of the reservoir is 400 litres. When testing the hydraulic motor, the hydraulic motor is installed in the test rig machine with its gear shaft connected with another gear shaft of the bent axis motor by chain coupling. When testing the dynamic efficiency, the repaired hydraulic motor has to rotate the load which is the bent axis hydraulic motor A2FM of 160 cc/rev. When it was driven it tend to be a pump as well as a load for testing. At port A and B of the pump, the hydraulic oil circulates through within the hydraulic bridge circuit (Graetz circuit) which consist of four cartridge check valves, proportional pressure relief valve (PRV) and charging system as seen in Figure 2.

At the start of testing the hydraulic motor, hydraulic oil ISO VG68 circulated from pump A2FM to block valve or hydraulic bridge circuit. There are two lines; the high pressure line (HPL) and low pressure line (LPL) with different pressure known as delta pressure (Δp). This circuit is similar to hydrostatic transmission whose major elements are pump (A2FM), motor (hydraulic bridge circuit or graetz circuit) and charge system.

Four check valves together with proportional pressure relief valve are mounted in the block valve, as seen in Figure 2. There are two ports A and B and another port connected to the charge pump and proportional pressure relief valve. This can control the pressure in charge line which corresponds with the flow and circulation of hydraulic oil or speed of load pump. The flow rate of hydraulic oil depends on the speed of rotation of the pump load. When the speed of pump load rotation increases, the flow rate of hydraulic oil also increases, leading to high pressure at proportional pressure relief valve. Also, when the speed of pump load rotation decreases, the flow rate of hydraulic oil decreases, but there will be no corresponding effect on the pressure.

When the loop-line flow rate is high, a pressure drop develops across the pressure control valve, generating a pressure differential and causing hydraulic losses that are converted into heat. The load on the hydraulic motor being tested is increased by increasing the pressure at the proportional pressure control valve. In hydraulic motor efficiency testing, the presence of pressure differentials and high flow rates leads to energy losses that result in elevated heat generation. The hydraulic oil temperature during volumetric efficiency testing of hydraulic pumps and motors should be maintained within the range of 33–60 °C, in accordance with ISO 4409. The hydraulic oil temperature in the low-pressure line during hydraulic motor efficiency testing exceeds 80 °C. This leads to the deterioration of the anti-wear additive performance. As illustrated in the original circuit in Figure 2, the hydraulic oil in the test circuit undergoes no cooling or filtration prior to returning to the reservoir, and only a limited amount returns via the load pump drain line. The reduction of hydraulic oil temperature and the filtration of hydraulic oil are improvements that should be implemented in this test rig. As discussed previously, the load-generating circuit in this efficiency test exhibits characteristics of a closed-loop system and can be improved by incorporating a flushing line to control hydraulic oil temperature and contamination. The improvement analysis of this circuit will be performed by treating it as a closed-loop system, with consideration given to the high-pressure line, low-pressure line, charge pump pressure and flow, flushing pressure and flow, and the cooling system. In the hydraulic bridge (Graetz) circuit, the flow through the pressure relief valve is unidirectional, and an additional flushing line on the low-pressure side should be connected downstream of the pressure relief valve. The criteria for adjusting the pressure and flow rate of the charge pump, as well as the flushing and cooling flows, are determined based on closed-loop circuit theory. Another proportional pressure relief valve dedicated to flushing is added to the low-pressure line downstream of the load-control proportional pressure relief valve, in order to control the pressure to match the charge pump pressure. Hydraulic oil temperature control within the specified range is achieved using a LabJack T7 Pro, which is employed to monitor key variables such as charge pressure, charge flow, flushing flow, and cooling temperature, and has been found to operate effectively.

Figure 1. Cross-sectional view of the repaired hydraulic motor installed in the test rig and connected as a load motor.



(a) (b)

Figure 2. (a) The original hydraulic circuit used in the hydraulic motor test rig (b) Modified hydraulic circuit incorporating flushing and cooling for the hydraulic motor test rig.

2. The temperature behaviours of the hydraulic oil in the load circuit used for hydraulic motor testing

In the investigation of temperature behaviours in the load-simulation system for a hydraulic motor, the system is treated as an integrated system comprising an A2FM hydraulic motor, a hydraulic bridge circuit, and a charge system. Measurements and data logging are carried out using the HMG 4000 data recorder and HYDAC pressure sensors and temperature sensor. Following testing conducted under ISO 4409 conditions to gain an understanding of temperature behaviours, improvements were then made to the circuit and control system and the hydraulic oil used in the test is ISO VG 68. To study the temperature behaviour caused by heat generation under variable pressure with constant flow rate and variable flow rate with constant pressure, the hydraulic system was operated in the configuration shown in Figure2. (a)and(b). The experimental results indicate that the thermal behaviour is governed by the fundamental energy balance equation

$$mc_p \frac{dT}{dt} = Q_{gen} - Q_{loss} \qquad (2.1)$$

During the experiments shown in Figures 4 and 5, the hydraulic system operated without active cooling, and the oil exchange with the reservoir was limited. Under these conditions, heat dissipation to the surroundings was relatively small, particularly during each constant operating stage. Therefore, the heat loss term Q_{loss} can be considered negligible compared to the generated heat, and the equation can be approximated

$$mc_p \frac{dT}{dt} \approx Q_{gen} \qquad (2.2)$$

The heat generation in a hydraulic system resulting from pressure losses can be expressed as follows

$$Q_{gen} = \Delta p Q \qquad (2.3)$$

The equation is applied to assess heat generation due to pressure losses arising from pump motor losses, throttling valve losses, and flushing relief losses that is employed to calculate the heat generation within the load-simulation loop of the test rig.

2.1 Hydraulic motor testing under no-load conditions.

In this test, a variable-displacement motor is employed as the load driver. Operating at 700 rpm, it produces a circuit flow rate of 130 L/min, with pressures of 27 bar in the high-pressure line and 6.6 bar in the low-pressure line, resulting in a pressure differential of approximately 20 bar. In the no-load test, the temperature rises linearly with a constant slope from 28 °C to 93.2 °C within 10 minutes at the low-pressure line, while the temperature at the high-pressure line reaches 90.7 °C, yielding a temperature difference of 2.5 °C. Although no load pressure is applied, the temperature increases to 93 °C due to the pressure differential between the inlet and outlet of the hydraulic bridge circuit, where the associated losses are converted into heat. Heat generation results from energy losses caused by flow resistance in drilled orifices, pressure drops across two check valves and the pressure relief valve, as well as valve throttling.

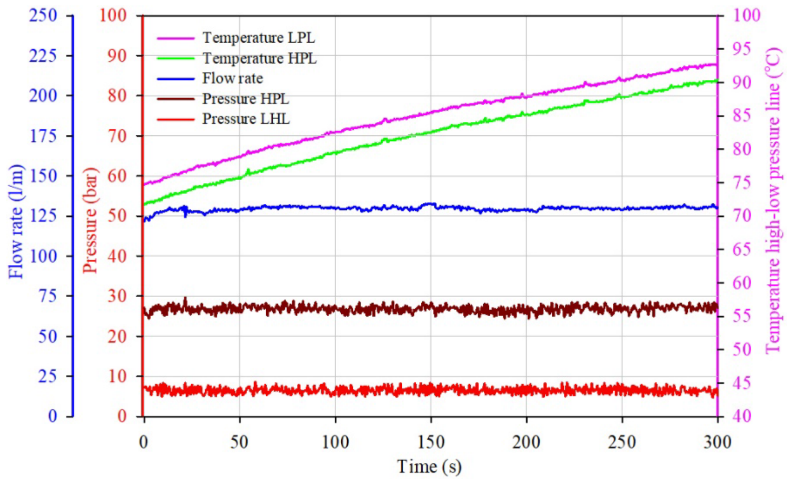


Figure 3. Oil temperature in the high-pressure and low-pressure lines at constant pressure and constant flow rate.

2.2 Hydraulic motor testing under constant pressure with increasing flow rate.

Hydraulic motor testing is performed under multiple operating conditions depending on the motor type and size, since different displacements result in different load capacities. Accordingly, testing is carried out under high-pressure, low-flow-rate and low-pressure, high-flow-rate conditions, and the temperature response due to heat generation under non-cooled conditions is presented in Figure 4. In the initial stage, the load condition was simulated at an operating pressure of 104 bar for 94 s. The pressure differential between the high-pressure and low-pressure lines was 86 bar, and the flow rate was 26 L/min, yielding a heat generation rate of 3.734 kW. In the subsequent stage, under a comparable operating pressure of 109 bar for 64 s, the pressure differential was 89 bar. With the flow rate increased to 42 L/min, the resulting heat generation was 6.242 kW. In the final stage of the graph, under an operating pressure of 101 bar for 10 s, a pressure differential of 81 bar and an increased flow rate of 62 L/min result in a heat generation of 8.386 kW. Despite the short duration, the high heat generation leads to a linear temperature rise with a pronounced slope. Although the pressure differential remains at a comparable level across the three stages, the increase in flow rate leads to a significant rise in heat generation from 3.73 to 8.39 kW, resulting in a linear temperature increase with a steeper slope, even over a short operating duration.

2.3 Hydraulic motor testing under constant flow rate with increasing pressure.

In this test, the initial flow rate was set to 47 L/min, while the hydraulic oil temperature was maintained in the range of 43.5–45.5 °C.

Table 2.1 Heat generation under constant pressure with increasing flow rate.

Stage	Δp HPL–LPL (bar)	Flow (L/min)	Time (s)	Heat generation (kW)
1	86	26	94	3.73
2	89	42	64	6.24
3	81	62	10	8.39

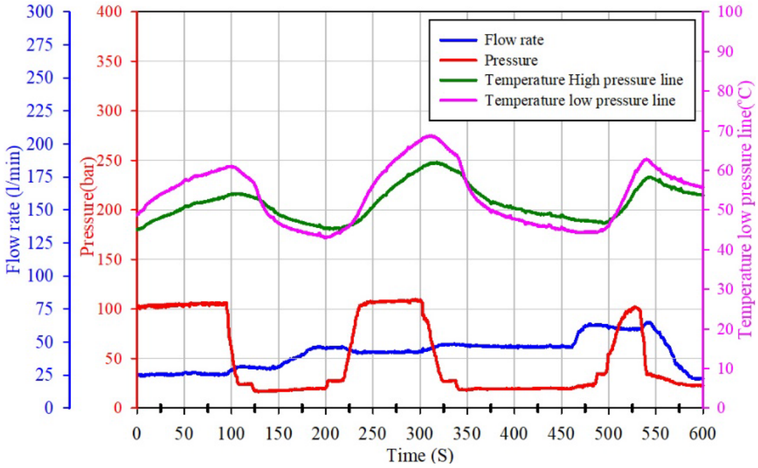


Figure 4. Oil temperature in the high-pressure and low-pressure lines under constant pressure with increasing flow rate.

During the first stage, the simulated load pressure was increased to 53.6 bar for 53 s, producing a pressure differential of 34.86 bar between the high-pressure and low-pressure lines and a corresponding heat generation of 2.74 kW. In the subsequent stage, the simulated load pressure was increased to 79 bar for 87 s. This produced a pressure differential of 61.3 bar between the high-pressure and low-pressure lines, resulting in a heat generation of 4.483 kW. In the final pressure stage, the simulated load pressure was increased to 105.5 bar for 88 s, producing a pressure differential of 88.4 bar between the high-pressure and low-pressure lines and a corresponding heat generation of 6.274 kW. During this period, the hydraulic oil temperature rose continuously to the range of 67.3–74.9 °C, as shown in Figure 5.

Table 2.2 Heat generate constant flow rate with varying pressure.

Stage	Δp HPL–LPL (bar)	Flow (L/min)	Time (s)	Heat generation (kW)
1	34.86	44.4	53	2.58
2	61.3	43.8	87	4.48
3	88.4	42.5	88	6.27

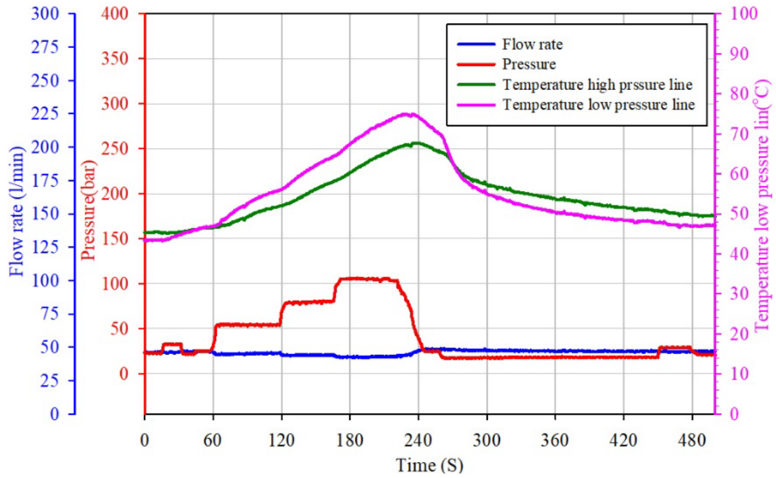


Figure 5. Oil temperature in the high-pressure and low-pressure lines at constant flow rate with varying pressure.

To study the temperature behaviour caused by heat generation under vary pressure with constant flow rate and vary flow rate with constant pressure, the hydraulic system was operated in the configuration shown in Figure 2(a). The experimental results indicate that the thermal behaviour is governed by the fundamental energy balance equation

2.4 Hydraulic motor testing under constant flow rate with increasing pressure.

As described in the preceding paragraph, the operating principle of the load-simulation circuit used for hydraulic motor testing is analogous to that of a hydrostatic closed-loop drive. The main distinction is that the hydraulic motor test circuit lacks a flushing system, whose function is to extract a portion of the high-temperature oil for cooling and filtration prior to its return to the reservoir or reintroduction into the loop. In response to the excessive hydraulic oil temperature in the loop circuit during testing, and based on the heat generation analysis revealing significant thermal generation over short operating durations, the test circuit was modified by incorporating a proportional pressure relief valve, an air cooler, a filtration unit, and a control system, as illustrated in Figure 2(b). The hydraulic oil from this section is returned to the reservoir. The modified circuit is installed downstream of the load proportional pressure relief valve on the low-pressure line of the loop.The parameter tuning is carried out in accordance with closed-loop circuit principles. Based on the original circuit configuration, the line equipped with proportional pressure relief valve No. 1 functions as the charge line supplying hydraulic oil to the loop. The charged oil flow rate is governed by the pressure setting of valve No. 1, whereas the drain flow from the load is negligible relative to the main loop flow. As a result, the charge pump is unable to supply sufficient oil to the loop. In accordance with closed-loop circuit theory, the charge flow rate should generally be maintained at approximately 20–30% of the main loop flow. This constitutes an additional cause of the heat generation observed in the previous graph.

To examine the charge flow supplied to the main loop, a test was performed as illustrated in Figure 6. Under a main loop flow rate of 28 L/min and a load pressure of 200 bar applied for 31 s, with the oil temperature rising from 33 °C to 57.3 °C and a charge pressure of 17 bar, the charge flow into the loop was limited to 0.89 L/min, representing only 4.45% of the main loop flow. Based on the test results, once the operating time exceeds 150 s, and at a charge pressure of 17 bar, the charge pump supplies hydraulic oil to the main loop at a flow rate of 7.25 L/min. This leads to a convergence of the cooling temperatures in the high-pressure and low-pressure lines, which is advantageous because it reduces thermal accumulation within the system.

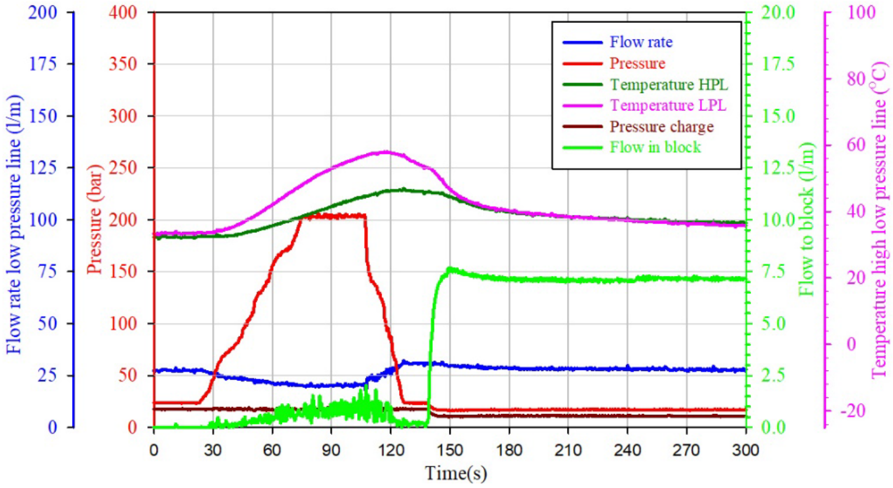


Figure 6. Measured charge flow rate of hydraulic oil supplied to the low-pressure line during testing.

From the study of heat generation in the load-simulation circuit, which is similar to a closed-loop system in mobile machinery, the pressure differential between the inlet and outlet of components leads to energy losses that are converted into heat. The heat generated in this system causes degradation of the hydraulic oil and subsequently leads to failure of hydraulic components. As a corrective measure, the circuit in Figure 2(a) should be modified to allow charge oil supply to the low-pressure line by installing a flushing line downstream of pressure relief valve No. 2, as illustrated in Figure 2(b). In the modified circuit, two proportional pressure relief valves are employed. Valve 1 is used to control the pressure of the hydraulic oil charged into the loop, whereas Valve 2 regulates the flushing line pressure, directing the oil through the cooler and filtration unit before returning it to the tank. In a closed-loop circuit, the charge pump pressure is adjusted to be slightly higher than the flushing line pressure. Both proportional pressure relief valves can be programmed and calculated based on Equation (2.1) to control the hydraulic oil temperature within the range of 33–60 °C under the following conditions.The equation used to control the proportional pressure relief valve.

$$\frac{\mathrm{dT}}{\mathrm{dt}} = \frac{\mathrm{Q_{gen}}}{mc_p} - \frac{hA}{mc_p}(T_{average} - T_{charge}) \qquad (2.4)$$

$$\frac{\mathrm{dT}}{\mathrm{dt}} = 0 \qquad (2.5)$$

$$\frac{\mathrm{dT}}{\mathrm{dt}} > 0 \qquad (2.6)$$

$$\frac{dT}{dt} < 0 \tag{2.7}$$

According to the conditions specified in Equations (2.5)–(2.7), the program can regulate the oil temperature, as demonstrated by the temperature results presented in Figure 7.

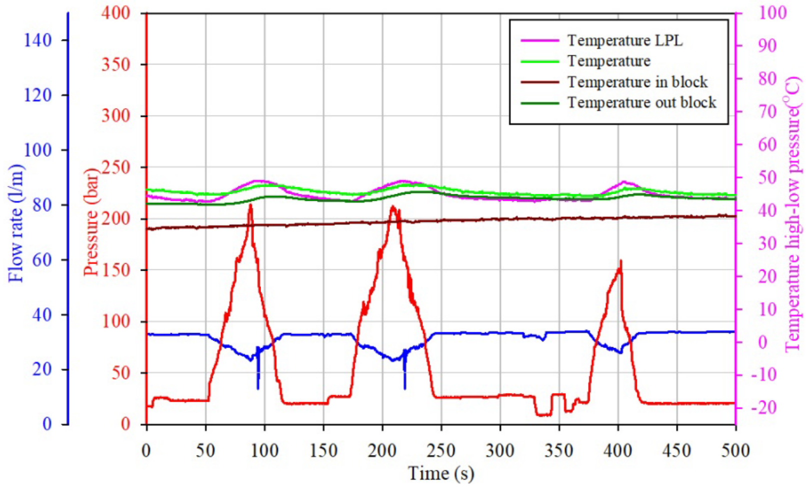


Figure 7. Temperature control achieved through the implementation of a flushing line and regulation of the charge pressure.

3. Conclusion

During no-load motor testing, it was observed that hydraulic oil still flows from the pump through the valve block, resulting in a continuous increase in temperature. This occurs because the high flow rate causes a significant pressure drop across the proportional pressure relief valve, leading to energy losses that are converted into heat.

Operating characteristics under high-pressure load and low-speed(low flow rate) conditions include a high pressure differential in the loop (high Δp) and a low flow rate (low Q). Under these conditions, heat generation is dominated by pressure-induced losses, resulting in a high heat generation per unit flow. Consequently, the loop temperature rises rapidly. High-pressure/low-speed operation therefore represents the worst thermal condition for a hydrostatic drive system.

Operating characteristics under high-speed and low-load conditions include a low pressure level in the loop and a high flow rate. In this regime, the pressure differential (Δp) is low, resulting in relatively small pressure-related losses. Internal leakage per unit time increases slightly, while viscous losses increase with speed. Overall, heat generation remains moderate. The high oil circulation rate enhances heat dissipation, leading to relatively stable loop temperatures with a small temperature difference between the loop and the tank. Flushing has a less pronounced effect compared to heavy-load conditions. In summary, high-speed/low-load operation represents a thermally stable condition.

The addition of flushing and programmed feedback control enables the mitigation of high hydraulic oil temperatures, particularly because hydraulic motor testing involves motors of various sizes and operating functions.

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Biographies

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