DETERMINATION OF ABILITY OF MACHINES WITH HYDRAULIC DRIVE DURING START-UP IN LOW AMBIENT TEMPERATURES

Ryszard Jasinski

Gdansk University of Technology, Faculty of Mechanical Engineering
Department of Hydraulics and Pneumatics
Narutowicza 11/12, 80-233 Gdansk, Poland
tel.: +48 58 3472932
e-mail: rjasinsk@pg.gda.pl

Abstract

Defining the principles and conditions of safe operation of hydraulically driven machines and devices is essential for their designers and operators. For this reasons the author did a series of tests of hydraulic components: axial piston pumps, external gear pumps, electro-hydraulically operated directional spool valve electrically operated directional spool valve, proportional valve, servo valve, relief valve, hydraulic low-speed motors: satellite, orbital motors, hydraulic cylinders and systems in thermal shock conditions (cooled-down component were supplied with hot working medium). In such conditions, starting parameters of the selected hydraulic component and systems which secured safety of their operation were determined. The experimental tests were carried out in the laboratory of the Chair of Hydraulics and Pneumatics, Gdansk University of Technology. During start-up of a hydraulic system in thermal shock conditions elements of hydraulic components warm up in a nonuniform way, due to varying material and shape properties. This causes change of clearances between the co-operating elements and may lead to faulty performance of hydraulic components and machine's break-down. The change of clearances may be evaluated by experimental, analytic or computer simulation methods. The evaluation of effective clearances between the co-operating elements of hydraulic components enables to foresee correct or incorrect operation of a system (or an component).

***Keywords**: hydraulic machines, hydraulic drives, diagnostics, hydraulic systems*

1. Introduction

Starting the hydraulic system at low ambient temperature can be performed using either cold or hot working medium, which is usually a hydraulic oil. The following cases of starting the hydraulic system at low temperature are possible (Fig. 1).

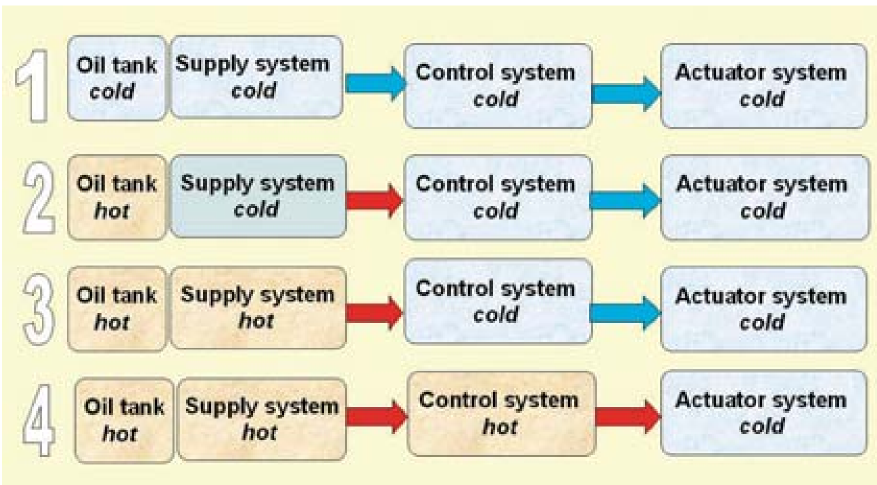

Fig. 1. Four cases of starting conditions of a hydrotronic system in low ambient temperature

1. at the instant of starting, all hydraulic component of the working machine have the same low initial temperature, which means that the working medium flows from the supply system to the cold control and executing component,
2. the oil in the tank is heated up, whereas the supply, control, and executing component are cooled down,
3. the temperature of the supply system is higher than that of the cooled-down control and executing component,
4. the executing component are cooled down, whereas the supply system and control component are of higher temperature.

In the 1st case, at the starting instant the complete hydraulic system together with the oil are of the same temperature as the environment, whereas in the remaining cases of system start-ups (i.e. cases 2, 3, and 4 above) the oil, just before its delivery to the cooled-down unit, is heated up to a temperature much higher than the ambient one. These are the conditions for the appearance of a thermal shock.

In heavy-duty machines, for instance those used for earth work, all cases of hydraulic system start-ups represented in Fig. 1 can happen. The bulldozer, shown in Fig. 2, contains two or more hydraulic systems. One of them is the drive system, responsible for supplying the motors which drive wheels or caterpillars. The other is the working system, which consists of a number of working components. The cooled-down motors (1) of the drive system may be heated up uniformly like the remaining component of the system, as a result of the loss of energy in the system (Case 1 in Fig. 1), or dynamically when supplied with the hot oil heated up in advance in a preliminary supply pump circuit (thermal shock conditions) (Case 4 in Fig. 1). The executing and control component (2) of the hydraulic working system of the bulldozer in question are exposed to thermal shock conditions corresponding to case 3 and 4 in Fig. 1.

The start-up of a system in winter conditions of low ambient temperature is characteristic of decreased efficiency of particular component and the entire machine, in which higher vibrations and noise are produced. In these very unfavourable conditions, shorter lifetimes and more frequent failures of the hydraulic component are observed.

For the above reasons the author performed tests of hydraulic component of various designs in low ambient temperatures. The tests made it possible to detect and describe the phenomena which take place in hydraulic component and systems during their start-ups in such conditions.

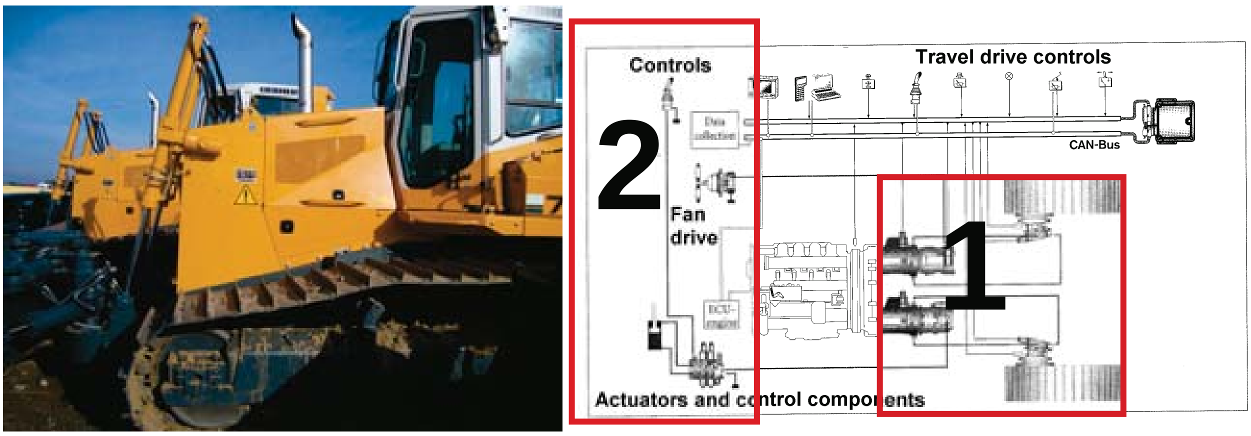

Fig. 2. Hydraulically driven bulldozer: 1 – drive system, 2 – working unit and fan systems [12, 17]

2. Research of machines with hydraulic drive starting in low ambient temperatures

The experimental tests of warming of Linde Hydraulics components of mobile hydraulic combine harvester Claas Mega 208 [18, 20] were executed in low ambient temperatures (Case 1 in

Fig. 1) [2, 11]. Besides Linde Hydraulics components, also components of Volvo, Steyer and Libherr are assembled in machine's hydraulic drive. The oil Renolin B HVI 46 Fuchs was used in the system.

Pumping unit is composed of principal variable displacement pump (axial piston pump with swash plate Linde BPV 100) and replenishing gear pump. Fluid stream from replenishing pump is steered through cooler and filter to the low pressure side of the closed loop circuit. Fixed displacement axial piston motor BMF 105 Linde is equipped with the flushing valve. Scheme of the hydraulic circuit with components is introduced in Fig. 3.

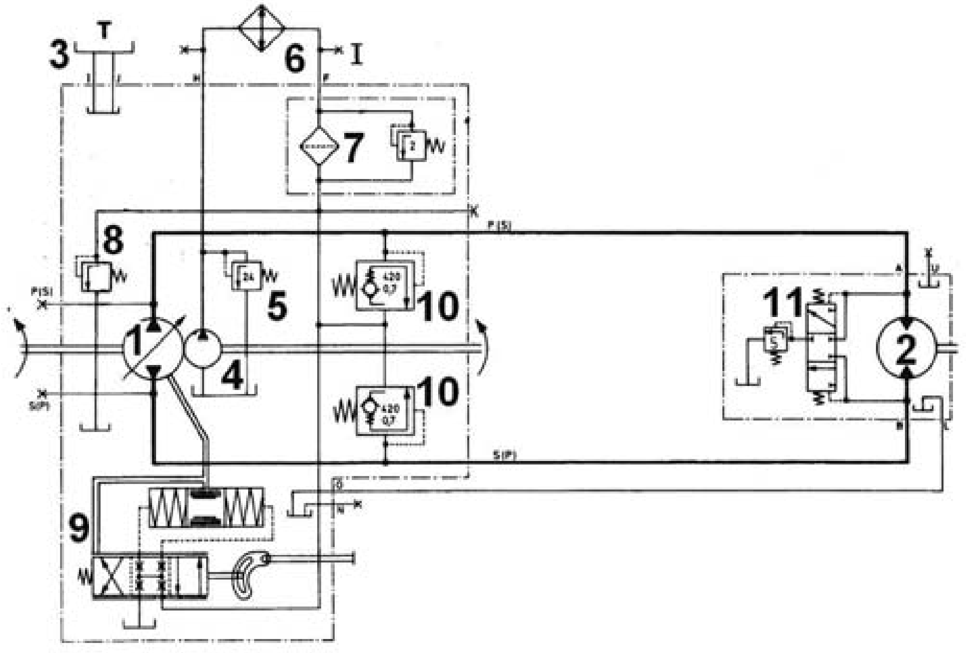

Fig. 3. Scheme of drive hydraulic system: 1- variable displacement pump, 2 – fixed displacement axial piston motor, 3 – tank, 4 – replenishing pump, 5- relief valve, 6- oil cooler, 7- filter, 8- relief valve, 9- control, 10 – check - relief valve, 11- flushing valve [18, 20]

Tests of warming process of hydraulic components were executed with thermal imaging infrared FLIR camera, measuring set HMG 3000 Hydac equipped with pressure, temperature and rotation speed sensors and turbine flowmeter.

A dozen or so tests were executed of hydraulic drive system during start up in low ambient temperatures (unloaded motor). One of them was executed for: ambient temperature -12,6^{0}C, flow rate in the closed loop circuits 156 dm3/min, pump's shaft rotation speed 1570 rpm.

After start up of hydraulic system thermal imaging of pump and motor warming up was executed (Fig. 4). On the base of the thermal images of heating pump courses of temperature of housing of pump (Fig. 5), housing of motor and difference of temperatures of oil on inlet and outlet from cooler ΔT_{ch} were determined (Fig. 5).

After start-up (T0, Fig. 5) of hydraulic system there comes a violent increase of pump (pump's housing) temperature caused by opening of relief valve 5 (Fig. 3), later (T1, Fig. 5), shutdown of the relief valve and directing of oil stream to cooler 6 (Fig. 3) caused the drop of temperature of pump. Since T2 (Fig. 5), stable process of heating of components of system is started.

During this test an incorrect working of drive system occurred. The reason of this was opening of the relief valve of drive system (time from T0 to T1, fig 5) as a result of large resistances of oil flow through cooler. Fluid stream from replenishing pump did not get to the low pressure side of the closed loop circuit, which could cause a damage of components in closed loop circuit.

During another start-ups drive system operated correctly for the following initial temperatures of drive system: - 1,1^{0}C, 3^{0}C, 6^{0}C (closed relief valve 5 (Fig. 3)).

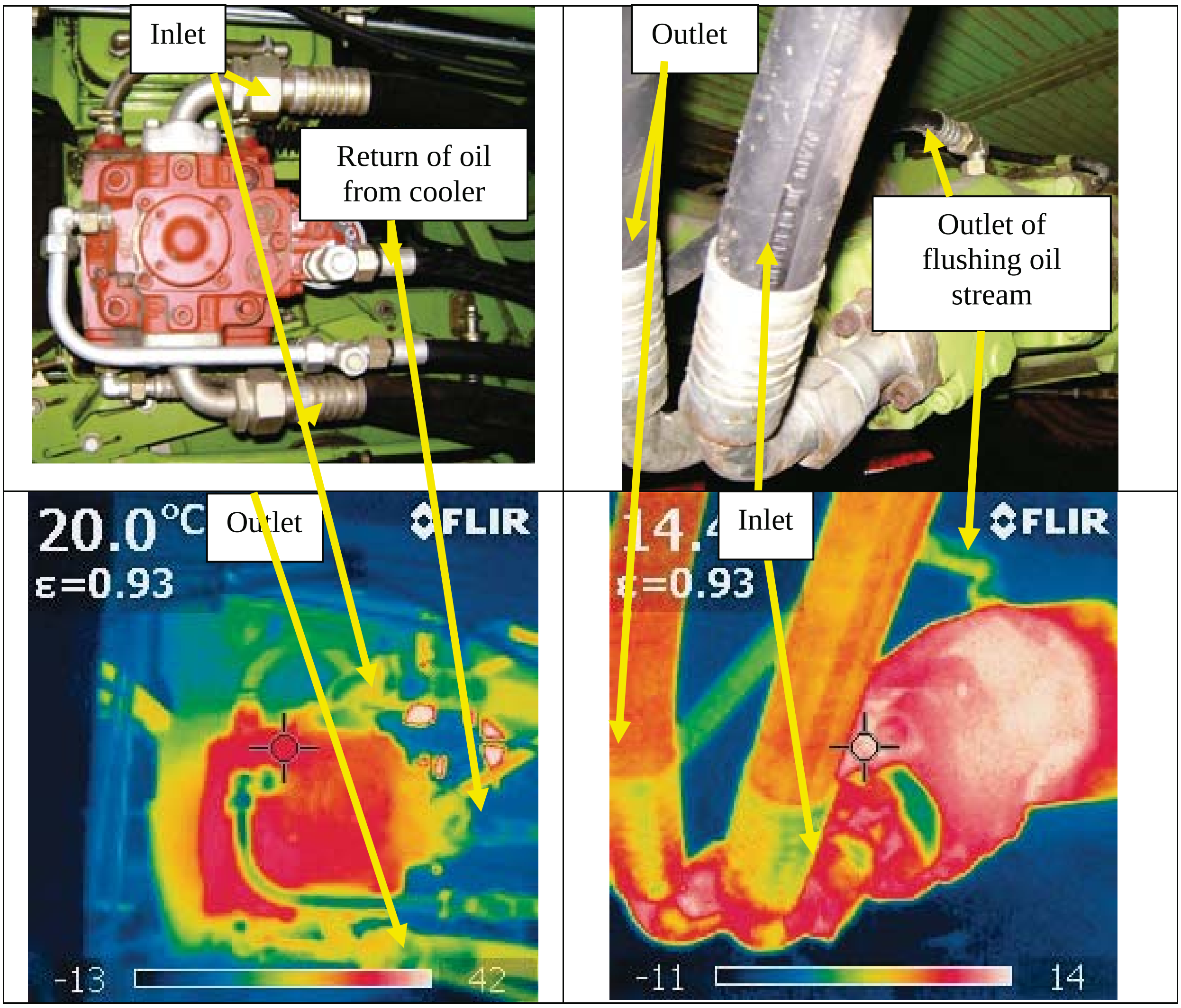

Fig. 4. Tested hydraulic components: pump BPV 100 and motor BMF 105 Linde and their thermal images [11, 18, 20]

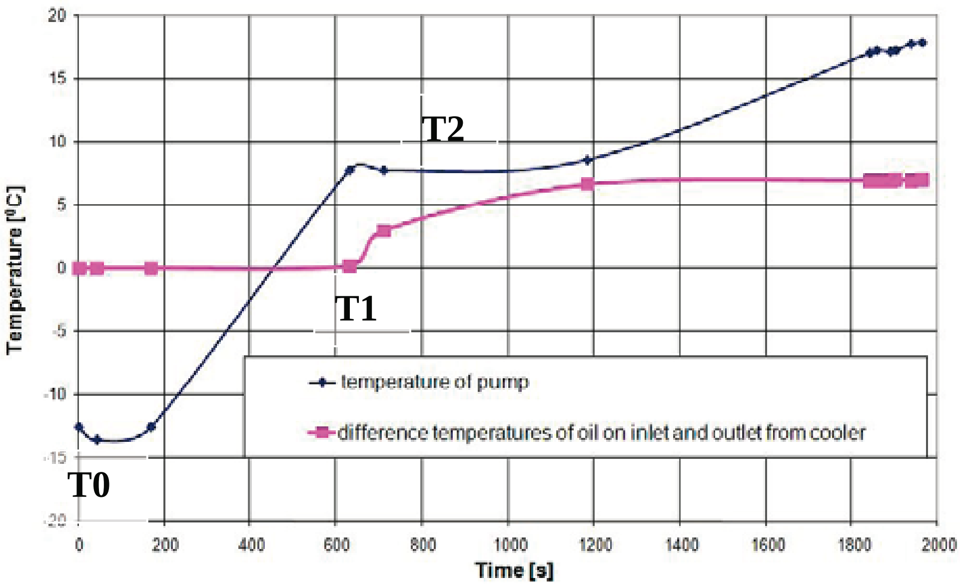

Fig. 5. Pump's housing temperature and difference of temperatures on inlet and outlet from cooler during start-up under following conditions: ambient temperature -12,6 ^{0}C, flow rate in the closed loop circuit 156 dm3/min, pump's shaft rotation speed 1570 rpm

3. Phenomena which occur in hydraulic components and systems during their start-up at low ambient temperature [1-9]

During the start-up of the system in thermal shock conditions, the effective clearance between the co-operating elements changes. When the temperature difference between the working medium and the cooled-down hydraulic unit is too high, the clearance may completely disappear, thus leading to the failure of not only the individual unit but also of the entire system. There are various designs of hydraulic components. Each design includes certain characteristic points (nodes) of co-operation between the elements in which the disappearance of the clearance can happen. Due to a huge variety of the existing design solutions, only the most commonly used hydraulic component of heavy-duty machines are presented in the article.

In the axial piston pumps and motors, e.g. those with cam-driven commutation unit (Fig. 6), as well as in the radial ones, the disappearance of the clearance between pistons and cylinders, between slipper and swash plate (in designs with hydrostatic support), as well as between particular elements of the commutation unit can take place.

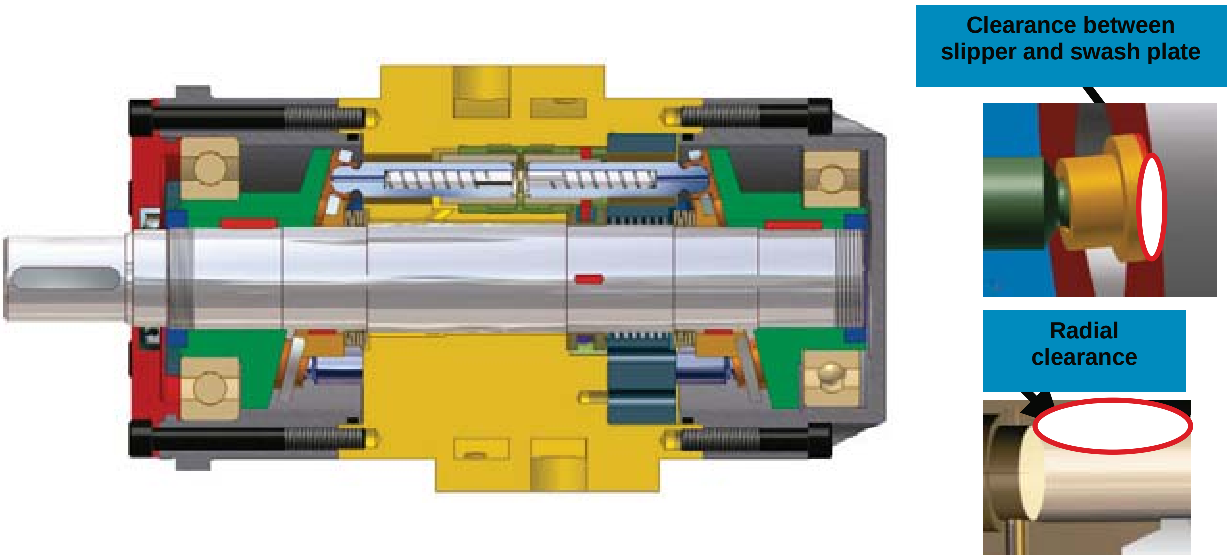

Fig. 6. PWK 27 axial piston pump [10, 13] with indicated places between co-operating elements where the disappearance of the clearance can occur

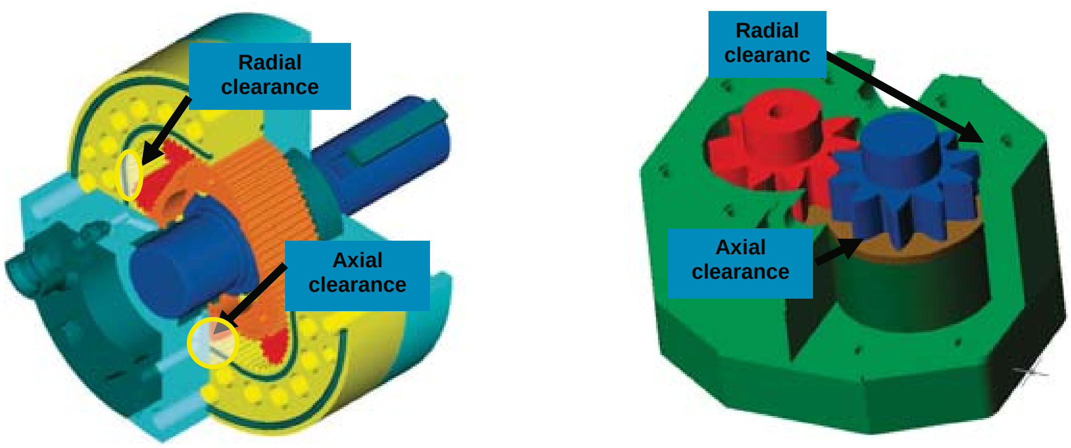

Fig. 7. SOK hydraulic satellite motor [14] with indicated places where the disappearance of axial clearance (between satellites and covers) or radial clearance (between satellite teeth and casing raceways) can take place, as well as a high-speed gear pump (motor)[13] with indicated places which are sensitive to thermal shock conditions

In gear pumps and motors the disappearance of the axial clearance between side surfaces of gear wheels and covers, or that of the radial clearance between tooth crests and the casing raceway can occur (Fig. 7). In the proportional directional spool valve it can come to disappearance of the clearance between casing and spool (Fig. 8).

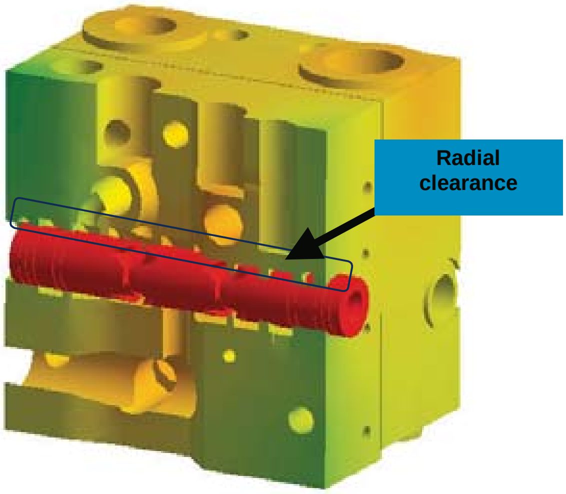

Fig. 8. PVG 32 proportional valve [16] with indicated places between co-operating elements (casing and spool) where the disappearance of the clearance can occur

4. Laboratory stand for testing hydraulic component in thermal shock conditions

Experimental tests have been conducted to detect phenomena taking place during the start-ups of hydraulic components: axial piston pumps, external gear pumps, electro-hydraulically operated directional spool valve, electrically operated directional spool valve, proportional valve, servo valve, relief valve, hydraulic low-speed motors: satellite, orbital motors, hydraulic cylinders in thermal shock conditions [2-9].

Fig. 9. Low-temperature chamber and measuring system installed in the laboratory of the Chair of Hydraulics and Pneumatics

The Chair's laboratory is equipped with, among other components, multi-pump supply devices fitted with oil temperature stabilization, devices for testing hydraulic components and systems, as well as the system for measuring and recording mechanical, hydraulic and thermal quantities.

The component were cooled down to the temperature of –25 (–38) °C, the minimum, in the low temperature chamber (Fig. 9, 10). The tests were carried out without forced air circulation. The temperature T1 of the oil supplying the motor was maintained within the range from 30 °C to 60°C (usually at 50 °C) using the oil temperature stabilization system.

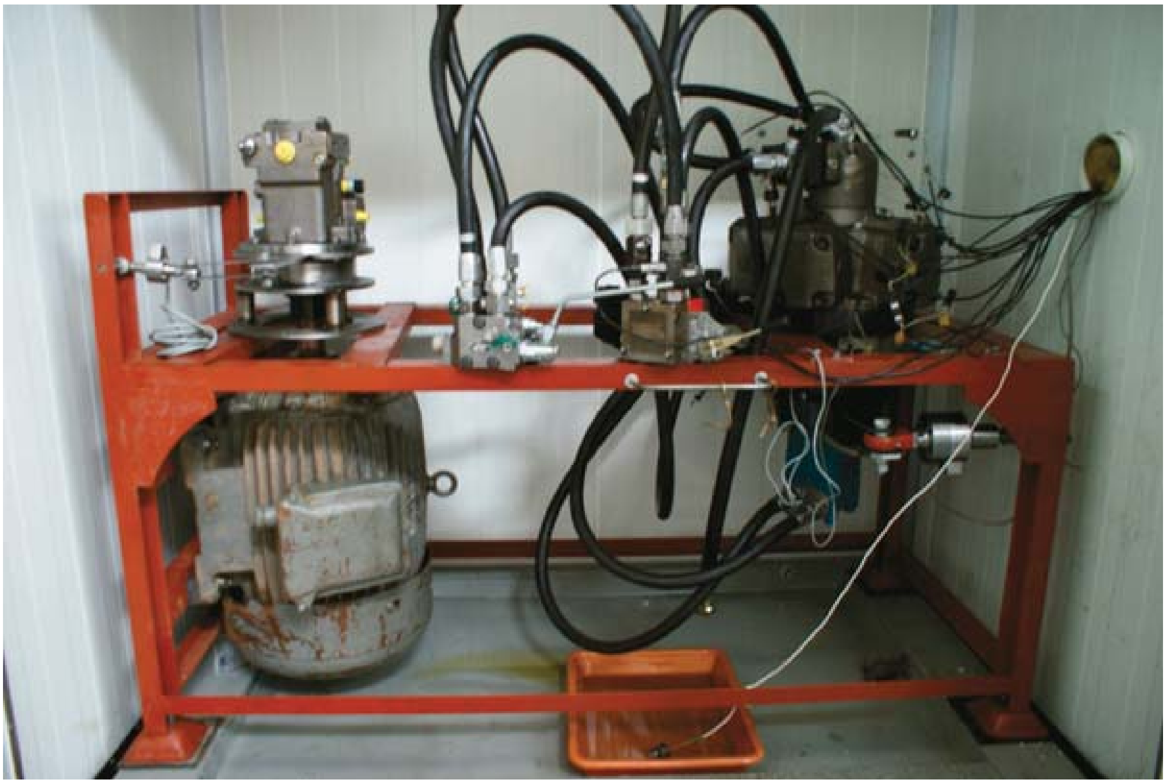

Fig. 10. Laboratory stand for testing hydraulic component [12-17] and system placed in the low temperature chamber

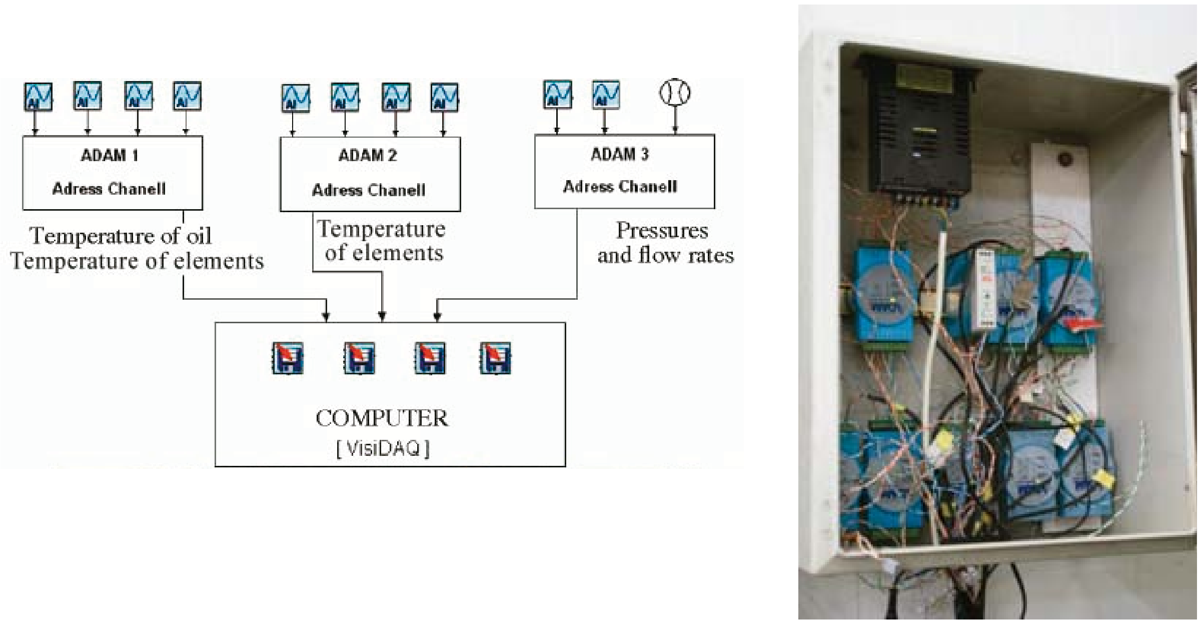

Fig. 11. System of transmitting and recording the data collected from sensors [19]

During the start-up of the hydraulic system the following quantities were measured:
$p_1(\tau)$ – pressure at hydraulic unit inlet, $p_2(\tau)$ – pressure at hydraulic unit outlet, $Q(\tau)$ – oil flow rate, $n(\tau)$ – rotation speed of pump motor shaft, T_{ot} – temperature in the cold chamber,
$T_1(\tau)$ – temperature at hydraulic unit inlet, $T_2(\tau)$ – temperature at hydraulic unit outlet,
$T_i(\tau)$ – temperatures at selected points of elements of the tested component, $M(\tau)$ – torque.

The Advantech Visidaq software [19] was used for collecting of the measured data in the computer-aided data transmission and recording system (Fig. 11).

5. Determination of the clearance between co-operating elements of the hydraulic component during its start-up in thermal shock conditions

Changes of clearances between co-operating elements of the hydraulic component during its start-up in the considered conditions depend on many factors: load, ambient temperature, oil temperature, oil flow rate. Fig. 12 presents the following quantities: l_0 – geometrical clearance, l_m – assembling clearance, l_e – effective clearance.

The geometrical clearance l_0 is determined by real dimensions of the co-operating elements. During the assembly of the hydraulic component, the geometrical clearance l_0 becomes smaller due to elastic deformations of the elements, Δl_m, resulting from the assembling grip.

The effective clearance l_e depends on the assembling clearance l_m, elastic deformation Δl_p of the hydraulic unit elements, which results from the oil pressure action, as well as on the difference Δl_t in the linear thermal expansion of the elements co-operating within the subsystem.

$$l_e(\tau) = l_m + \Delta l_p(\tau) - \Delta l_t(\tau) \,. \tag{1}$$

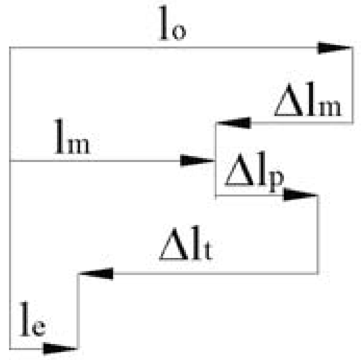

Fig. 12. Dimensional analysis for determining the effective clearance between co-operating elements of hydraulic component in thermal shock conditions

The pressure contributes to the increase of the clearance. The higher the pressure in component chambers, the greater increase of the effective clearance resulting from the elastic deformation of the elements of the hydraulic component $\Delta l_p(\tau)$, when it is supplied with the oil in thermal shock conditions.

The author of the present article has worked out a method for assessing changes of the clearance l_e in the considered starting conditions [2, 3].

6. Methods to define the areas of correct and incorrect work of hydraulic systems in thermal shock conditions

The characteristics registered during experimental research on heating of components of hydraulic systems as well as worked out methodology of data handling makes it possible to determine changes of the effective clearance during the starting period.

It is possible to determine the clearance height with several methods (Fig. 13):
– experimental,
– analytical,
– numerical computer simulation.

These methods allow to qualify whether a hydraulic component (system) will or will not work correctly.

Numerical calculations of heating of the elements of hydraulic components, requires assumption of some preconditions. One of them is heat transfer coefficient between oil and surface of heated element, which author has evaluated. Computer simulation of heating-up of the component's elements, allows interpreting the phenomena that occur in the systems under research, especially to determine the clearance changes during start-up. It is possible to establish the conditions for safe operation.

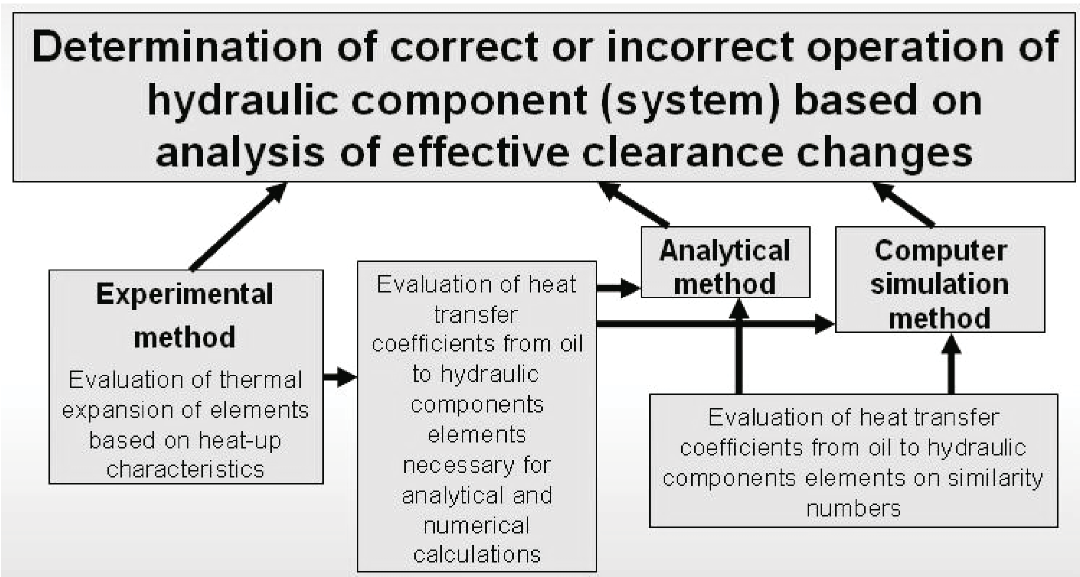

Fig. 13. Methods of effective clearance evaluation

Figure 14 presents results of computer simulation of temperature distribution in proportional valve PVG 32 during thermal shock conditions in 5th and 40th second after start-up.

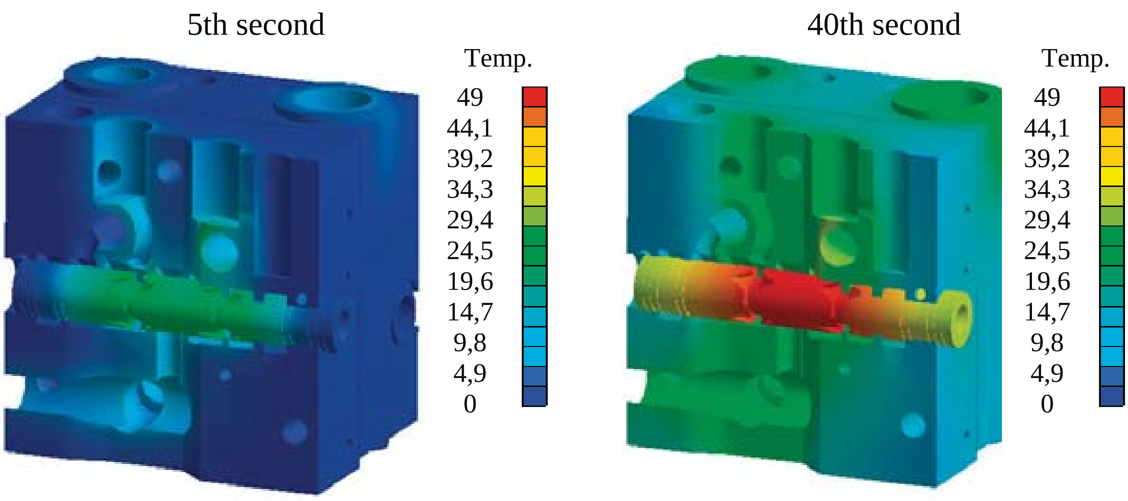

Fig. 14. Temperature distribution in proportional valve PVG 32 during thermal shock conditions in 5th and 40th second after start-up (flow rate Q = 32 dm^3/min, initial temperature 0 ^{0}C, oil temperature 49 ^{0}C)

7. Areas of starting parameters of selected hydraulic component in thermal shock conditions

On the basis of the tests of SOK 100 satellite motor (Fig. 7), PWK 27 pump (Fig. 6) the areas of their starting parameters were determined. They are defined by jumpwise increase of oil flow rate and difference between oil temperature and that of the hydraulic unit at the initial moment.

It was assessed that the SOK 100 satellite motor (Fig. 7) having axial clearance of 23 μm can operate correctly (Fig. 15) at the temperature difference between the oil and the cooled-down motor equal to 55 °C and the maximum oil supply flow rate. Motor start-ups at higher temperature differences may completely reduce the clearance and lead to the failure of the motor and the entire hydraulic device. The transient area „B" (Fig. 15) is inclined by a small angle to the vertical axis.

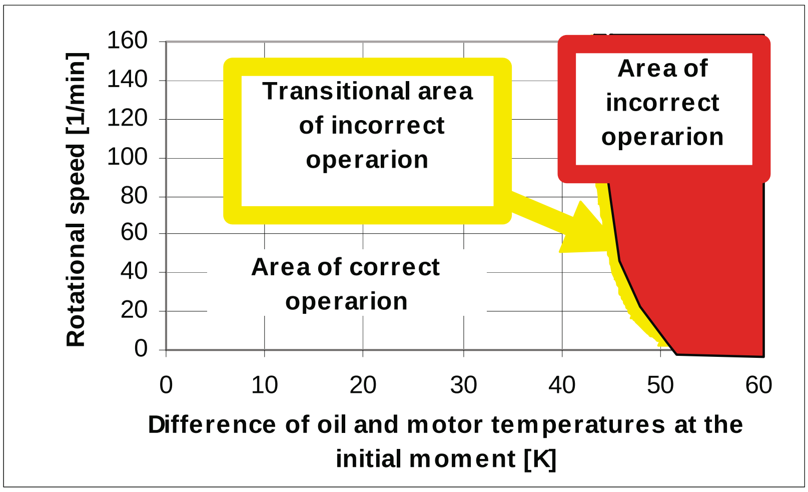

Fig. 15. Areas of operation of SOK 1600 motor with initial effective clearance of 51μm in thermal shock conditions

As a result, the smaller the jumpwise change of the flow rate, the higher the possible initial difference between oil and motor temperatures (area A) at which the motor is still able to operate correctly.

The tests of the PWK27 pump have revealed that during the start-up it operated incorrectly in some conditions. It was the case when the start-up was carried out at the pressure on the delivery side of the pump, equal to about 5 MPa, and the rotation speed exceeding 1500 rpm (Fig. 16).

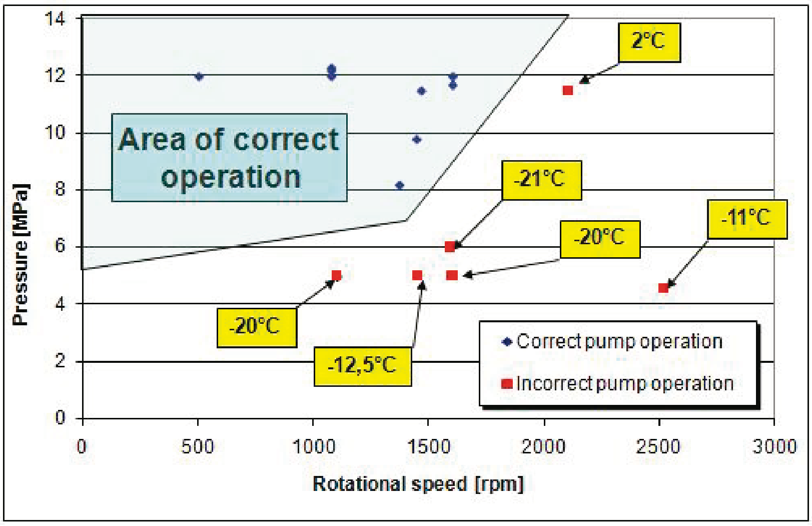

Fig. 16. Starting parameters of PWK27 pump in thermal shock conditions

During the initial period of the pump start-up its incorrect operation was manifested by instantaneous lack of hydrostatic support in the area of co-operation of the hydrostatic slipper and the swash plate. The incorrect operation of the PWK 27 pump in thermal shock conditions can be avoided by the use of an appropriate valve located behind the pump, in order to raise its pressure up to 5 MPa at least.

8. Conclusions

- The clearance between the co-operating elements is the main constructional factor which affects the operation of a hydraulic component in thermal shock conditions. Due to the heat exchange process, moving elements of the components are heated faster by the flow of hot oil than the casing (motionless element). Different linear deformations of particular elements are the reason why the effective clearance may be reduced to zero during component heating. The lack of clearance results in the appearance of dry friction between the moving and motionless elements. As a result, the produced heat is directly transferred to the elements. The temperature of the moving elements suddenly increases, which makes their dimensions even bigger. During this time the moving elements rotate irregularly, thus causing permanent failures of both the moving and motionless elements. The phenomena which most affect the operation of the component in thermal shock conditions occur during the first two minutes of the start-up process.
- The performed tests of hydraulic component in thermal shock conditions showed the way in which a given unit may behave in extreme conditions of operation.
- On the basis of the data (containing values of heat transfer coefficients, between oil and swilled element, dependent on oil velocity) it is possible to determine, with computer simulation (numerical program) or analytic method, the range of parameters (oil flow rate and temperature difference between oil and hydraulic component temperatures) for correct operation of hydraulic components (systems) in thermal shock conditions (Fig. 17) .

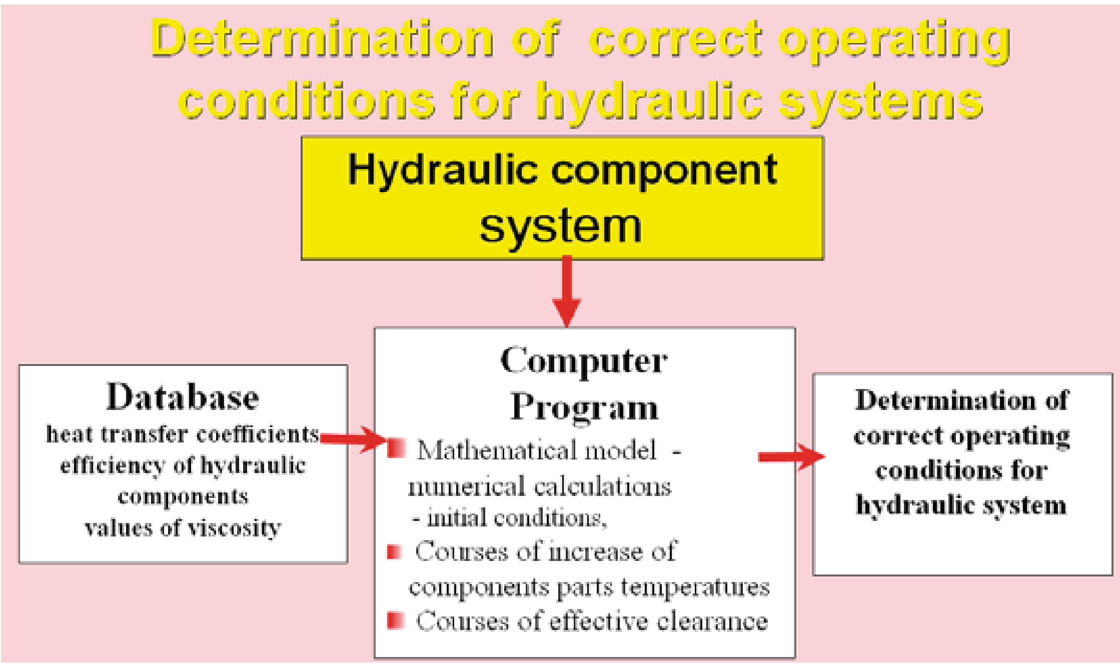

Fig. 17. Determination of correct operating conditions for hydraulic components or systems

The method (numerical program) for determining the area of correct operation of the hydraulic component (system) in thermal shock conditions might be very useful for designers.

References

[1] Balawender, A., *Energy analysis and testing methods of low speed hydraulic motors,* Scientific Bulletins of Gdansk University of Technology, Gdańsk, 1988.

[2] Jasiński, R., *Operation of low-speed hydraulic motors in thermal shock conditions,* Doctoral dissertation, thesis supervisor, A. Balawender, Gdańsk, 2002.

[3] Jasiński, R., *Research methodology of low speed hydraulic motors in thermal shock conditions*, the IXth Seminar „Drives and control 2003", Gdańsk, 2003.

[4] Jasiński, R., *Analysis of permissible start-up parameters for hydraulic motors in thermal shock conditions*, the Xth Seminar „Drives and control 2004", Gdańsk, 2004.

[5] Jasiński, R., *Operation of hydraulic system control components in low ambient temperatures when supplied with hot working fluid*, the IIIrd International Technical Diagnostics Congress „Diagnostic'2004", Poznań, 2004.

[6] Jasiński, R., *Operation of hydraulic components in low ambient temperatures*, Scientific Conference, Mechanika 2005, Gdańsk, 2005.

[7] Jasiński, R., *Assessment of suitability of hydraulic control components operated in low ambient temperatures*, conference papers: Diagnostic'2008, Olsztyn, 2008.

[8] Jasiński, R., *Experimental research of the multi-piston axial pump PWK 27 from HYDROTOR company in low ambient temperatures*, Drives and control, journal No. 4/08, 2008.

[9] Jasiński, R., *Methods of determination of correct operation area for hydraulic component in low ambient temperatures,* Developments in Mechanical Engineering, Gdańsk, 2008.

[10] Osiecki, L., *Multi-piston pumps with cam distribution,* Seminar papers „Drives and control 2003", Gdańsk, 2003.

[11] Cibiorski, W., *Ability of vehicle of hydraulic system working in different climatical conditions.* Graduation paper, thesis supervisor R. Jasiński, Gdańsk University of Technology, 2008.

[12] Books and catalogues from Bosch Rexroth company

[13] Catalogues from Hydrotor company

[14] Catalogues from ZUO Hydroster company

[15] Catalogues from Parker company

[16] Catalogues from Sauer-Danfoss company

[17] Catalogues from Liebherr company

[18] Catalogues from Claas company

[19] Catalogues from Advantech company

[20] Catalogues from Linde company