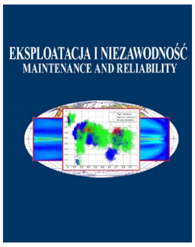

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Experimental testing of the influence of the operating loading on the flow characteristics of hydraulic pump

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Highlights

- The operating torque load is used to simulate the real operation of hydraulic circuits.
- The laboratory testing simulated the operational loading for 200 hours.
- The flow rate increases for 150 hours.

Abstract

The contribution deals with the influence of the operating loading on the flow characteristics of the hydraulic pump under laboratory conditions. In the test, a new toothed hydraulic pump and hydraulic oil with kinematic viscosity at 40°C, ν = 64.2 mm^2.s^{-1} were used. The operational loading was measured during the most difficult agrotechnical operation – ploughing, at which the loading of the hydraulic pump is the greatest. Laboratory testing was determined for 200 hours, and the flow characteristics had been detected at 50 hours intervals. Measurement of the flow characteristics was performed at rated speed n = 1,000 rpm. Measurement of the flow characteristics was carried out in dependence on the loading pressure from p = 0 MPa to p = 20 MPa. When p = 0 MPa, the value reached n = 91.70% and when p = 20 MPa, n = 86.68%. Running-in of the hydraulic pump lasted 150 hours, with an increase of the flow characteristics $\Delta\eta_{vol}$ = 1.36% (p = 10 MPa) compared to the initial state. After working for 200 hours, the flow rate of the hydraulic pump decreases compared to 150 hours.

Keywords

hydraulics, hydraulic device, flow efficiency

1. Introduction

Hydraulic circuits have the major impact on the operation of tractors. The flow efficiency of the hydraulic pump significantly influences the efficiency of the tractor and auxiliary equipment. The purpose of this paper is to monitor the impact of difficult agrotechnical operation (ploughing) on performance of the hydraulic pump under laboratory condition. Hydraulic pump is a type of hydraulic machine, according to [17] and as like a transmission system, have an extensive use in agricultural technology due to its wide design capabilities, high efficiency in power transmission and speed regulation. The laboratory testing was carried out on the experimental laboratory equipment constructed at the Department of Transport and Handling, Faculty of Engineering, SUA in Nitra. Hydraulic equipment is widely used in powerful mechanisms of agricultural and forest machines as well as in many other areas. The development of the modern hydraulic components is aimed at increasing of transmitted power, reducing the energy intensity, minimizing the environmental pollution and increasing the technical life and machine reliability [4].

By simulating load conditions such as temperature change, constant or operating pressure change, flow change, degradation of operating fluids, which can be precisely defined on the basis of the physicochemical properties of liquids, occur [13]. Because of this, they use accelerated hydraulic components and fluids testing in laboratory conditions to simulate operational conditions, usually specified by a standard [21].

Universal tractor transmission oils (UTTO) are developed for hydraulic and transmission systems of agricultural tractors [27]. These fluids provide lubrication function in the gear box and transmission of energy in the hydraulic system of the tractor [2].

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Hydraulic system is important part of agricultural tractors, which are used to transfer power from internal combustion engine to attachments, and at the same time to control the tractor's three-point hitch [23]. Hydraulic pump, as one of the main parts of whole hydraulic system, is used to convert mechanical energy into pressure energy [18, 25]. To prevent accidental failures or to prolong the technical service life of hydraulic pump, methods of technical diagnostics are used [24]. The process life of hydraulic pump, as well as operational reliability, is primarily affected by the process of operational loading [12].

To determine the technical service life and reliability, laboratory tests of hydraulic pumps are used, which can be divided into:

- constant torque loading,
- torque loading with step torque,
- moment loading with sinusoidal characteristics,
- loading with transient torque changes,
- load with operating torque.

The operating torque load is used to simulate the real operation of agricultural tractor's hydraulic circuits. When simulating the load, it is appropriate to use the loading characteristics of the hydraulic circuits under the most difficult operating conditions, which is, in case of agricultural tractors, ploughing [26]. To simulate the operating conditions, it is advisable to use an electro-hydraulic proportional valve.

For the technical diagnostics of hydraulic pumps, it is necessary to monitor the flow characteristics changes, and the flow efficiency calculated from those characteristics [16]. The flow efficiency of the hydraulic pump determines its technical service life and operational reliability [20].

The importance of technical diagnostics of hydraulic pump lies in the monitoring of flow characteristics, which can be considered as predictive maintenance of hydraulic pumps [10]. A decrease in flow characteristics signals a fault [29]. An important parameter in evaluating the flow characteristics of a hydraulic pump is the dynamic viscosity, which can significantly change flow efficiency [28].

It is possible to simulate real operating conditions by laboratory tests, in which the load on operating torque is used. The importance of the laboratory test mentioned in the presented paper lies in the prediction of the hydraulic circuit operation's, based on real working conditions [22].

In the presented paper, a laboratory test of a universal fluid used in the transmission-hydraulic circuits of agricultural tractors was performed. The conditions of the laboratory test are based on the operating conditions of the hydraulic pump load. During the test, the influence of the operating load on the flow characteristics of the hydraulic pump, which are the basic characteristics of the life of the hydraulic pump, is monitored.

The importance of the laboratory test of the universal fluid is based on the possibility of applying the tested universal oil in the transmission-hydraulic circuit of the tractor. Prior to the actual application, the universal fluid is subjected to a laboratory test based on the operating conditions of the tractor's hydraulic transmission circuit. In the laboratory conditions, the operating conditions of the transmission-hydraulic circuit of the agricultural tractor are simulated. Simulation of operating conditions allows laboratory tests to be performed under constant conditions.

The total laboratory test time is set at 200 hours. During this time, the hydraulic pump will be loaded with operating pressure. The pressure in the hydraulic circuit creates an electrohydraulic proportional valve.

2. Materials and method

2.1. Laboratory testing – conditions

The determination of the laboratory conditions was based on the loading characteristics of the hydraulic pump of the tractor. The operational loading was measured during agrotechnical operation – ploughing. This characteristic defines the process loading of the hydraulic pump. Measurements of these characteristics were carried out by placing the pressure sensor on the output of the hydraulic pump. The measurements took 200 seconds. The characteristic is shown in Fig. 1. From the measured data, we have established basic statistical data (Table 1).

Table 1. Basic statistical data

	Unit	Value
Mean	MPa	8.95025
Standard Error	MPa	0.22159
Median	MPa	8.57
Mode	MPa	13.45
Standard Deviation	MPa	3.13372
Sample Variance	MPa	9.82023
Kurtosis		-1.1222
Skewness		0.09475
Range	MPa	10.54
Minimum	MPa	3.57
Maximum	MPa	14.11
Count		200
Confidence Level (95.0%)		0.43696

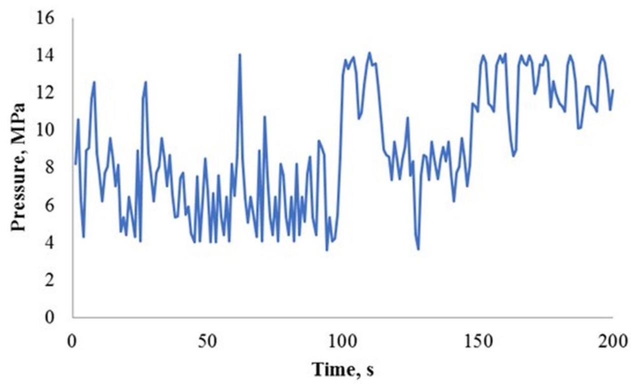

Fig. 1. Operational characteristics of the loading of the hydraulic pump

Table 2. Technical data of the hydraulic pump

Parameters		Unit	Amount
Geometric volume		dm^3	17.39E10^{-3}
Operating speed	nominal	rpm	1,500
	minimum	rpm	350
	maximum	rpm	3,200
Admission pressure	minimum	MPa	-0.03
	maximum	MPa	0.05
Discharge pressure	minimum	MPa	31
	maximum	MPa	32

From this characteristic, the loop was created and an electro-hydraulic proportional valve (EHPV) was programmed for experimental laboratory device (Fig. 2). Technical data of hydraulic pump are given in Table 2.

A)

B)

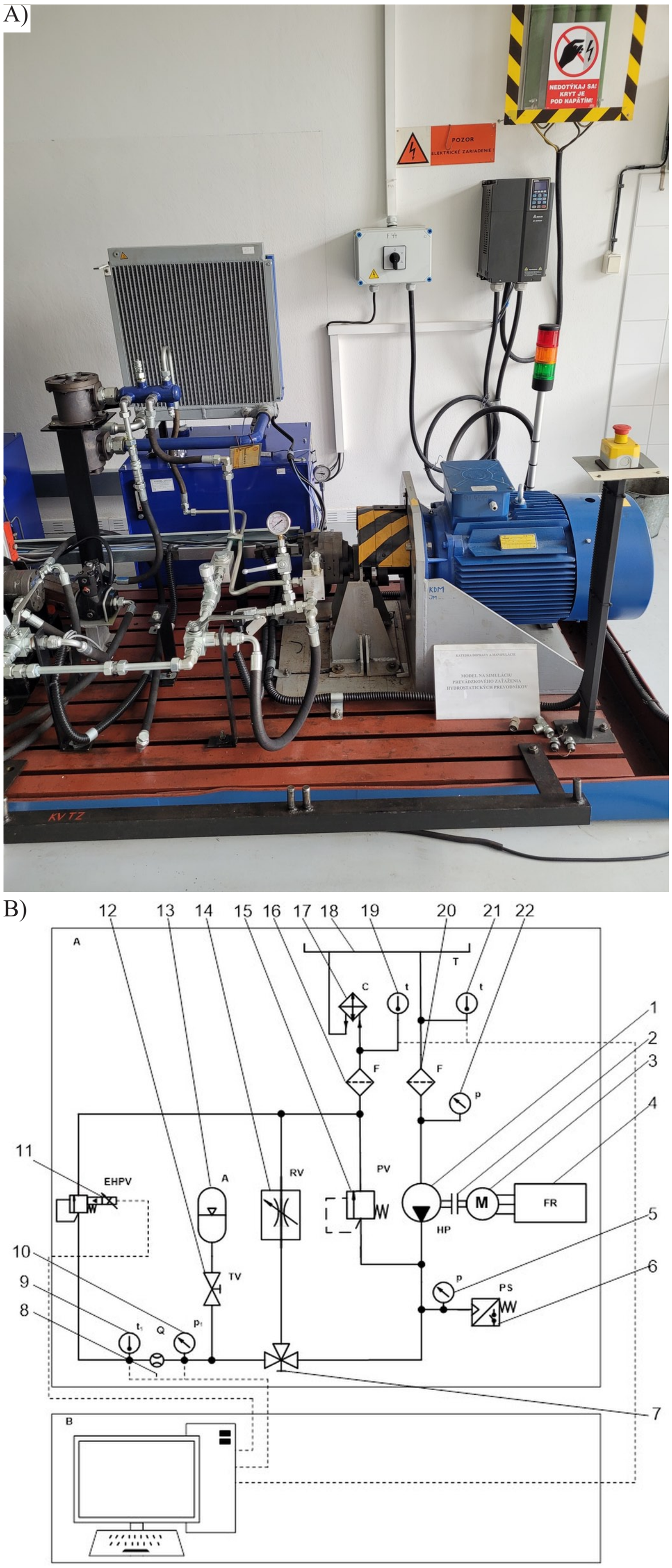

Fig. 2. Scheme of the experimental laboratory testing device: (A – Hydraulic circuit, B – Control and assessment circuit, 1 – hydraulic pump, 2 – coupler, 3 – electric motor, 4 – frequency converter, 5 – pressure sensor, 6 – electric pressure sensor, 7 – three-way valve, 8 – flow rate sensor, 9 – temperature sensor, 10 – pressure sensor, 11 – electro-hydraulic proportional valve, 12 – throttle valve, 13 – pressure accumulator, 14 – reducing valve, 15 – pressure valve, 16, 20 – filter, 17 – cooler, 18 – tank, 19, 20 – temperature sensor, 22 – pressure sensor)

The laboratory testing device is powered by an electric motor (3) that is connected to the frequency converter (4), in order to achieve constant speed. The hydraulic circuit is secured against overloading by pressure valve (15) mechanically and by electric pressure valve (6) electronically. To monitor operational level, the hydraulic circuit is equipped with temperature sensors (9), (19), (20), pressure sensors (5), (10), (22) and the flow rate sensor (8). The hydraulic circuit is also equipped with a pressure accumulator (13) to dampen pressure flushes. The accumulator is turned on by throttle valve (12). Reaching of operational temperature or simulating of higher thermal loading of selected power carriers is done by an isolated reducing valve (14) that is controlled via three-way valve (7). The tank (18) is equipped with the inlet filter (20), as well as the outlet filter (16). To maintain the required operational temperature, the hydraulic circuit is equipped with a cooler (17). The electro-hydraulic valve (12) in the hydraulic circuit cyclically applies the loading on the gear of the hydraulic pump (1). Proportional throttle valve was used by [7]. Synthetic universal tractor oil (UTTO type), made on mineral base oils and SAE 80W viscosity class, and was applied in the hydraulic circuit. The basic technical data is shown in Table 3.

Table 3. Oil specification

Properties	Unit	Amount
Density at 15°C	kg.m^{-3}	875
Kinematic viscosity at 40°C	mm.s^{-2}	58.9
Kinematic viscosity at 100°C	mm.s^{-2}	10.2
Flash point	°C	210
Pour point	°C	−36

[9] defines hydraulic pump with external gear mechanism comprises two gears (driving and driven wheel) with involute gears. The liquid is transferred from the suction branch to the displacement, the amount of the displaced liquid being dependent on the geometric volume determining the pumped volume of the liquid per revolution of the hydraulic pump. The overall efficiency of the hydraulic pump varies according to [19] in the range of 0.8 to 0.95, with an increased level of noise caused by pressure peaks, compression of the fluid during the rotation of the sprockets of the hydraulic pump.

2.2. Conditions for measuring of the flow characteristics

Measurement of the flow characteristics was performed with experimental laboratory device (Fig. 2) every 50 hours. While measured, the oil temperature was 40° C, in accordance with ISO 8217: 2012.

Measurement of the flow characteristics was carried out according to the loading pressure of p = 0 MPa, p = 20 MPa, at intervals of p = 5 MPa. Measurement of the flow characteristics was performed at nominal speed of the generator n = 1,500 rpm.

2.3. Rating of the dynamic viscosity

Brookfield D2VT viscometer was used to evaluate the dynamic viscosity. the Julabo ED5 Circulation Thermostat was used to set the stable temperature of ± 0.03°C. According to ISO 8217:2012 for lubricating and hydraulic fluids, the measurement of kinematic viscosity at 40°C was determined. For conversion to kinematic viscosity, the Mettler Toledo DM40 laboratory grade in LiquiPhysics^{TM} Excellence series was used. ISO 15380: 2011 sets upper respectively lower limit of the kinematic viscosity change at 40°C by ± 20%.

3. Laboratory test results

Figure 3 shows the flow characteristics of the hydraulic pump in dependence on the pressure by individual operating hours. According to [6], the measurement of the flow characteristic is used to determine the effect of the hydraulic fluid on durability of the hydraulic pump.

The decrease of the flow characteristics of the hydraulic pump depends on the pressure drop at the hydraulic pump. According to [21] the theoretical flow of the hydraulic pump is determined:

$$Q_T = V_G.n = q_f.2\pi.n = q_f.\omega \qquad (1)$$

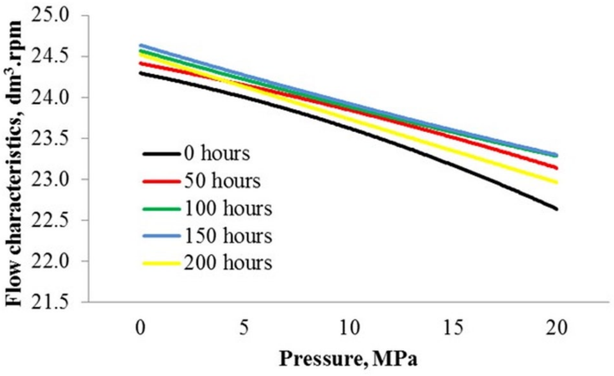

Fig. 3. Flow characteristics of the hydraulic pump

Then the actual flow of the liquid depends on the kinematic viscosity and the pressure gradient:

$$Q_R = Q_T - Q_L = Q_T - \frac{V_G.\Delta p}{\mu} = q_f.\omega.\eta_{vol} - \frac{V_G.(p_t - p_v)}{\mu} \quad (2)$$

The pressure drop of the fluid with respect to pressure (Figure 3) corresponds to the formula for determining the actual flow of the liquid (2). The dependence of the pressure drop on the fluid pressure was found by [11]. They found approximately 20% pressure drop depending up the pressure, which corresponds to the data measured during testing. Flow efficiency is reduced by spacing between the gears and the wear of bearing blocks of the hydraulic pump. According to [14], based on the geometry of the teeth spaces, the kinematic viscosity of the oil, the predominant laminar flow, the flow losses are caused by spacing between the gears and the hydraulic pump block and the teeth tips depending on the pressure drop of the hydraulic pump. Based on the Hagen-Poiseuille formula, the loss of the hydraulic pump depending on the pressure drop can be established [5]:

$$Q = \frac{dV}{dT} = V.R^2.\frac{\Delta p}{l} = \frac{b.h^3.\Delta p}{12.\mu.l} \quad (3)$$

In the Fig 4 - 7 the flow efficiency is shown and the drops of the flow rates depending on the individual pressures. Promising outcome correlation $R^2 = 1$ (in all measurements) was reached with the 4th polynomial interpolation function:

$$y = a.x^4 + b.x^3 + c.x^2 + d.x + f \quad (4)$$

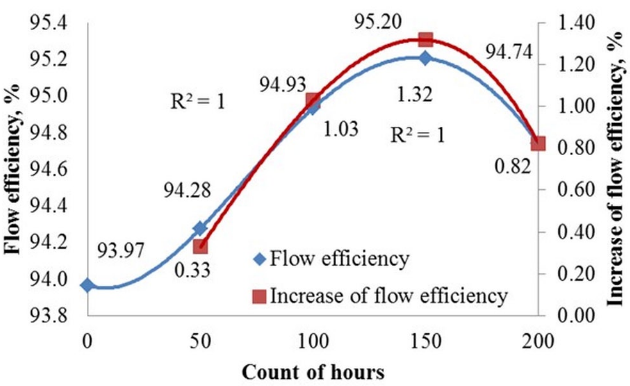

Fig. 4. Flow efficiency and increase of the flow efficiency at pressure p = 0 MPa

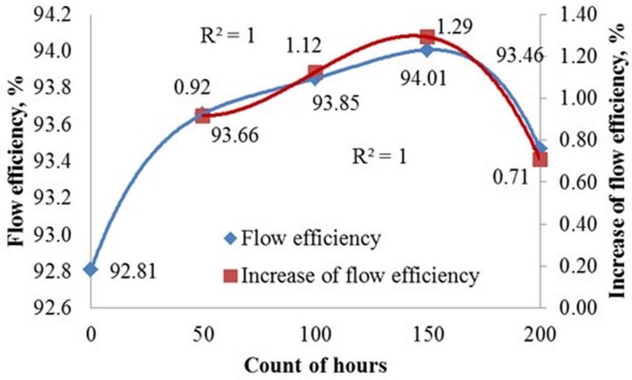

Fig. 5. Flow efficiency and increase of the flow efficiency at pressure p = 5 MPa

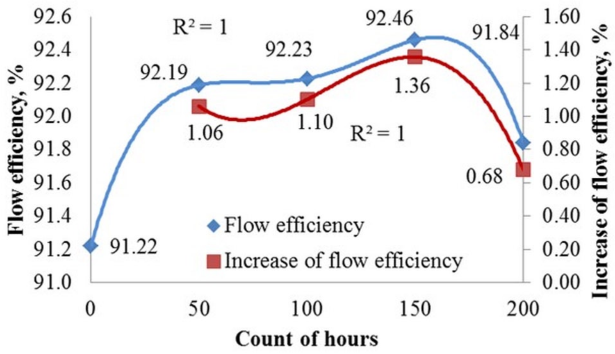

Fig. 6. Flow efficiency and increase of the flow efficiency at pressure p = 10 MPa

As we can see on the pictures, the lowest value of the flow efficiency was found at the beginning of the laboratory test (0 hours). Individual flow rate detection was detected at different pressure values (p = 0 MPa, p = 5 MPa, p = 10 MPa, p = 15 MPa, p = 20 MPa). From the data, we can see the dependence of the decrease of the flow efficiency of the hydraulic pump in correspondence on the loading pressure. At the beginning of the laboratory testing, with pressure p = 0 MPa, the flow efficiency was n = 90.48% and with p = 20 MPa, the value of the flow efficiency is n = 84.04%. The flow rate increases for 150 hours. When p = 0 MPa, the value reached n = 91.70% and when p = 20 MPa it was n = 86.68%. After 200 hours of operation, the flow rate of the hydraulic pump decreases compared to 150 hours operation.

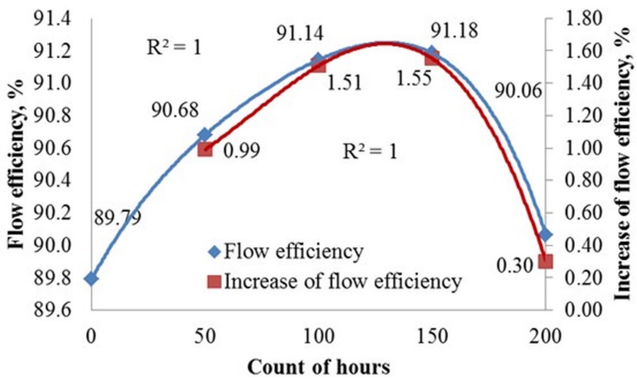

Fig. 7. Flow efficiency and increase of the flow efficiency at pressure p = 15 MPa

Fig. 8 shows tendency of the kinematic viscosity to change at 40°C under laboratory condition. According to [15], kinematic viscosity is one of the most important properties characterizing the lubricants and their transport properties and is a criterion of internal friction of the

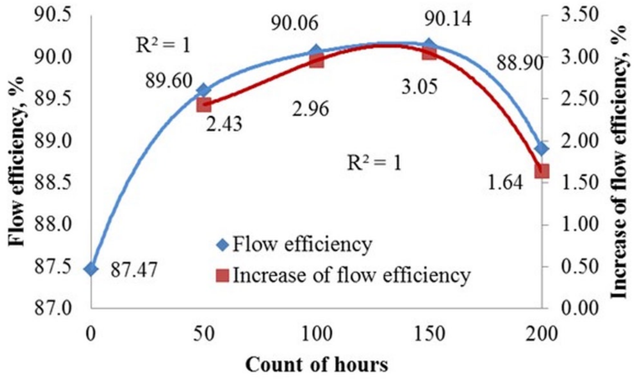

Fig. 8. Flow efficiency and increase of the flow efficiency at pressure p = 20 MPa

fluid. At the same time, [8] states that the kinematic viscosity determines the flow tendency of the liquid to withstand flow.

3.1. Exclusion of the impact of the dynamic viscosity changes

Based on formula (2) which determines the actual flow of the liquid depending on the dynamic viscosity, the theoretical flow of the liquid was calculated. Based on determining the theoretical flow efficiency of the hydraulic pump, with depends on dynamic viscosity an comparison with the calculated flow efficiency (calculated from the measured values of flow characteristics – Figure 9) there is a minimal effect of dynamic viscosity on changes in the flow rates of oil (Figure 10). The change of flow rate values occurs especially due to the pressure drop of the hydraulic pump.

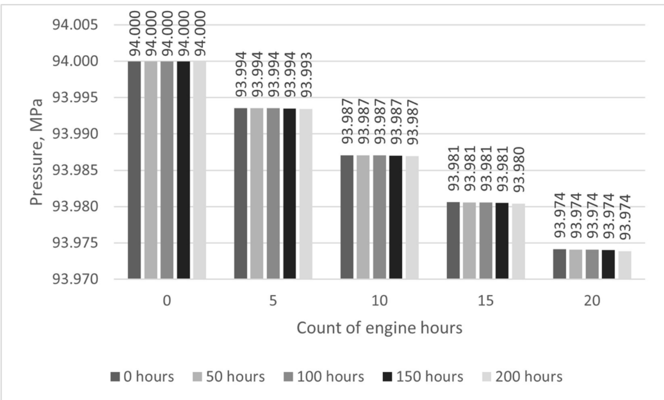

Fig. 9. Theoretical flow rate depending up to dynamic viscosity changes

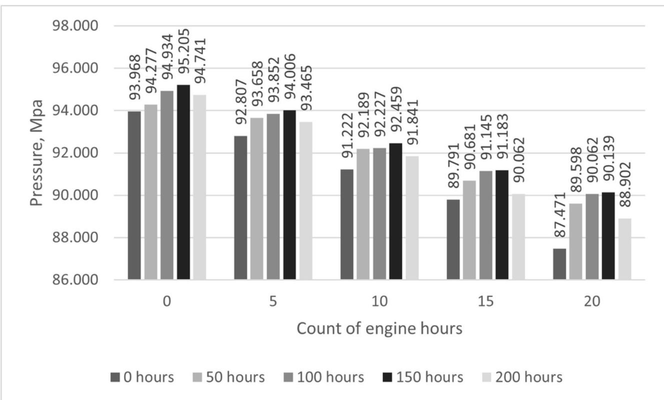

Fig. 10. Actual (measured) flow efficiency

4. Discussion

As can be seen from Fig. 3, by increasing loading, the flow of the liquid (flow efficiency) decreases. The decreasing flow rate characteristics is linear and is caused by increasing loading of the bearing blocks. Dobrota et al. [6] found that at the rated speed of the hydraulic pump and the gradual increase of the loading by 20% of the maximum pressure (after 80% loading of the hydraulic pump), the hydraulic pump shows the drop of flow about 1.5%. This fact corresponds to the data which had been found (Fig. 3). The influence of the increasing loading on the decrease of the flow characteristics was published by [1]. Decrease of the flow in dependence on the increasing pressure results from formula (3).

From the point of view of the evaluation of the laboratory testing, the value of the flow efficiency when p = 10 MPa is the most significant. This value approximates the mean value of the operational loading of the hydraulic pump shown in Fig. 1 (*p = 8.95 MPa* or median *p = 8.57 MPa*). According to [6], the flow characteristics measurements and the subsequent calculation of the flow rates are used to determine the effect of the hydraulic fluid on durability of the hydraulic pump. When pressure is p = 10 MPa (pressure gradient) and working time is 0 hours, the flow rate achieved is $\eta_{vol} = 91.22\%$. After 50 hours of laboratory testing, there was an increase of the flow efficiency $\Delta\eta_{vol} = 1.06\%$ from achieved value $\eta_{vol} = 92.19\%$. After 150 hours, the flow rate gradually increased compared to the initial state $\Delta\eta_{vol} = 1.36\%$ from achieved value $\eta_{vol} = 92.46\%$. Increase of the flow efficiency is caused by running-in of the hydraulic pump. The running-in of the hydraulic pump is caused by the reduction of the spacing between the bearing blocks of the hydraulic pump. After 200 hours, there was a decrease of flow efficiency $\Delta\eta = 0.70\%$ compared to 150 hours, when it achieved the value $\eta_{vol} = 91.84\%$. It can be stated that after 150 hours the process of running-in of the hydraulic pump was terminated and the hydraulic pump was operating in operation mode. According to [17], the process of wearing and tearing is caused by the spacing between the gears and the hydraulic pump. After 200 hours, an increase of the flow efficiency was observed compared to the start of the laboratory testing when $\Delta\eta_{vol} = 0.68\%$. The increase was caused by reducing the spacing between the bearing blocks of the hydraulic pump. The decrease of kinematic viscosity after 200 hours of laboratory testing was $\Delta v = 1.09\%$. This means that the limit value set by ISO 15380: 2011 has not been reached. Rundo [21] found a change of kinematic viscosity at 40°C on three samples of liquids $\Delta v = 1$ *to 8%*. The testing was determined for 90 hours on the basis of DIN 51562: 1999. Paeglis et al. [19] found a change of kinematic viscosity at 40°C in liquid samples when different additives were applied $\Delta v = 1.5$ *to 11.7%*. Laboratory testing were determined for 96 hours. Despite the various conditions of the liquid assay, it can be concluded that similar changes in kinematic viscosity at 40°C were found, as reported by [3].

5. Conclusion

The laboratory testing simulated the operational loading of the hydraulic pump for 200 hours. During the testing, the influence of the loading on the flow characteristics and hence the flow efficiency of the hydraulic pump was monitored. Running-in of the hydraulic pump lasted 150 hours, with an increase of the flow characteristics $\Delta\eta_{vol} = 1.36\%$ (p = 10 MPa) compared to the initial state. At same time, dynamic viscosity (calculated from kinematic viscosity at 40°C) was determined and its impact on the change in the flow efficiency of the hydraulic pump was excluded. The minimal effect of changing of the dynamic viscosity on the flow efficiency had been demonstrated. At the same time, the loss of the hydraulic pump was demonstrated, depending on the pressure drop, based on the Hagen-Poiseuille relationship. The laboratory testing is used to determine the running-in of the hydraulic pump based on operational loading, when running-in had been demonstrated.

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