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RESEARCH

Evaluation of Hydraulic Resistance in Various Liquids and Temperature

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ABSTRACT

This paper deals with a methodology for measuring and evaluating the static characteristics of control valves, with specifying a recommended measurement chain. This method enables measuring and evaluating the dependence of pressure drop on flow and flow coefficients depending on the type of fluid, temperature and viscosity also if the measurements were made at a different temperature and viscosity. This method extends of the possibility of using of these characteristics in the design work on hydraulic components in various areas of operation.

1. INTRODUCTION

When using hydraulic components, it is often necessary to have the characteristics Δp = f(Q) (pressure drop–flow), which are obtained from the catalogue of hydraulic components, or they must be determined by measuring. Catalogues specify these dependencies for certain temperatures or for certain types of fluids (eventually for temperature, density and kinematic viscosity of fluid). When applying these components in hydraulic circuits, we need to convert the relationship Δp = f(Q) for other types of fluid and for other temperatures[1]. Similar is the case when these characteristics are obtained by measurement. The typical representatives of hydraulic resistance to movement are the components shown in Fig. 1, e.g. a) restrictor, b) check valve, c) filter, d) cooler, and d) control valve, but also other components containing hydraulic resistance to movement.

The current trend of industries demands for those machinery which carry both high speed and load. Hydro-dynamic journal bearings are extensively used in high speed machines to support the shaft which runs in these machineries [2]. The following text contains the methodology for measuring the static characteristics Δp=f(Q) of hydraulic resistance to movement to be able to evaluate the characteristics depending on the fluid used and for selected temperature. Actual measurements are performed with different hydraulic fluids and temperature. Also biodegradable fluids belong to the group of fluids [3,4].

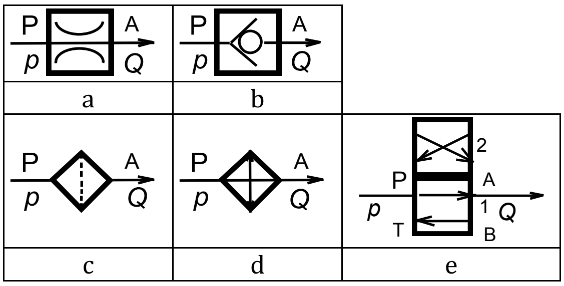


Fig. 1. Types of elements for measurement of p–Q characteristic (a–restrictor; b–check valve; c–filter; d–cooler; e–control valve).

A universal test device for research and educational purposes has been built at the Department of Mechanical Engineering, Faculty of Special Technology, University of Trenčín, allowing the measuring of some static and dynamic characteristics of hydrostatic pumps, restrictors, pressure valves and control valves for flows up to 28 dm^3min^{-1} and for pressure up to 5 MPa. The test device is supplemented with measuring probes, the measuring kit HMG 3000 and the evaluation software of the Hydac Company. The universal design of the test device is shown in Fig. 2.

2. MATERIALS AND METHODS

To demonstrate the methodology for measuring the hydraulic resistance to movement, these characteristics were measured on a four-way, two-positional hydraulic control valve. For the purpose of measuring static characteristics, the universal test device was modified according to Fig. 3. The hydraulic scheme of circuit connection for measuring the characteristics of the four-way, two-positional hydraulic control valve (HR) is given in Fig. 3. The device contains only a hydrostatic pump (G1); the output from hydrostatic pump (G2) to reduce the warming of fluid in the tank was interconnected to the tank (N). Pressure on the hydrostatic pump G1 and G2 was set to a value less than 5 MPa. The four-way, three-positional control valve (HR1) with mechanical button control is for switching the pressure measurement by a pressure gauge (M) in the first and second hydraulic circuit.

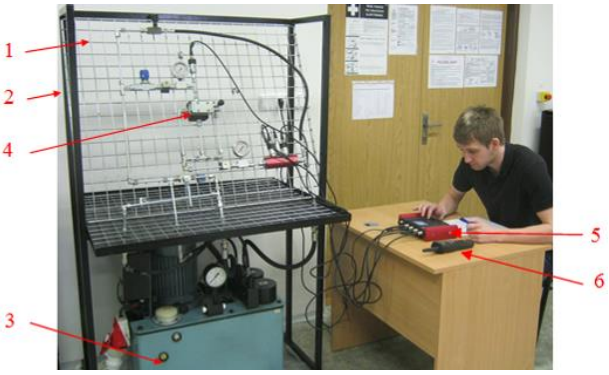


Fig. 2. View of universal hydraulic device (1 – grate surfaces; 2 – frame of device; 3 – hydraulic aggregate; 4 – measured hydraulic control valve; 5 – measuring unit HMG 3000; 6 – measuring unit of temperature and humidity).

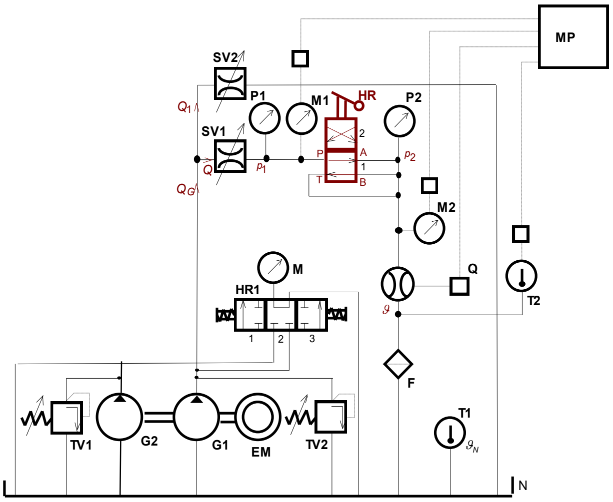


Fig. 3. Connection of hydraulic circuit for measuring the characteristics of hydraulic control valves (EM – electric motor; G1, G2 – hydrostatic pumps; N – tank; TV1, TV2 – pressure relief valves; HR1 – button hydraulic control valve for measuring of pressures by manometer M; F – filter; HR – measured hydraulic control valve; SV1, SV2 – restrictors; T1 – thermometer in tank; T2 – temperature sensor ϑ; P1, P2 – checking manometers; Q – flow meter; M1, M2 – pressure sensors p_1, p_2; MP – measuring and recording unit; Q_G, Q_1, Q_2 – flow of hydrostatic pump, branched flows; p_1, p_2 – pressures before and after hydraulic control valve HR).

The measuring circuit according to Fig. 3 consist in one branch from the hydrostatic pump G1, adjustable restrictor SV1, measured four-way, two-positional, manually operated hydraulic control valve HR, and flow meter Q. The output is interconnected to the tank N. The second parallel branch passes through the second restrictor SV2 directly into the tank N. The flow of the hydrostatic pump *Q* was branched in one branch to flow *Q1* and in the second branch to flow *Q2*; flow *Q2* passing through the hydraulic control valve HR. The procedure for branching of flow is as follows. At the beginning, the restrictor SV1 is closed, and the restrictor SV2 is fully opened. Firstly, the restrictor SV1 is gradually opening to the maximum; then, the restrictor SV2 is gradually closing to the maximum. This results in flow *Q2* from zero to the maximum. A reverse procedure is used to determine the hysteresis. Design of hydraulic circuit was by authors [5,6]

The measuring unit MP records pressure *p1* by the sensor M1, pressure *p2* by the sensor M2, flow *Q* and temperature of fluid ϑ by the temperature sensor T2. The manometers P1 and P2 are used for visual monitoring of pressures *p1* and *p2*. At the same time, ambient air temperature and humidity was measured by the measuring unit 6 according to Fig. 2.

For the design of hydraulic device's components, the following most important components with a 6 mm diameter were used:

EM – electric motor 3 kW/1440 rpm;

G1– geometric volume of hydrostatic pump 19 cm^3; real flow of hydrostatic pump 23.75 $dm^3 \cdot rpm$;

TV2 – maximum pressure 5 MPa;

HR – hydraulic control valve RSP-062J157-1;

SV1 – restrictor ST 0600G Italy;

SV2 – restrictor Dn O6 FESTO;

Q – flow meter EVS 3100-H-5, (1.2÷60) $dm^3 \cdot rpm$;

MP – measuring unit HMG 3000-000-E;

M1 – pressure gauge HDA 4748-H-0100-000, (0÷100) MPa;

M2 – pressure gauge HDA 4748-H-0009-000, (−1÷9) MPa;

T2 – temperature sensor ETS 4548-H-000 (0÷100) °C.

2.1 Methodology for measurement and evaluation

Measurement was performed using the measuring chain with the pressure sensor M1 – pressure *p1*, pressure sensor M2 – pressure *p2*, flow meter Q – flow *Q*, thermometer T2 – temperature of fluid in circuit ϑ, and the measurement unit MP according to Fig. 3.

Positions 1 and 2 to measure on the way P→A and P→B were gradually adjusted on the hydraulic control valve HR according to Fig. 3.

At the beginning of measurement, the restrictor SV1 was closed, and the restrictor SV2 was fully opened. The measuring chain was prepared with the measuring unit HMG 3000-00-E. The measuring interval of 20 ms was used for static measurement. The record in the measuring unit MP was activated. The restrictor SV1 was mechanically opening to the maximum. The record was completed. During the following measurements (reverse procedure), the restrictor SV2 was opening to the maximum, and the restrictor SV1 was subsequently closing. The record was completed. This measuring procedure was repeated several times. This branching of flow contributed to reaching the flow measured by the hydraulic control valve in the range of flow ($0 \div Q_{max}$). Measurements for increasing the flow from 0 to Q_{max} and subsequently to continuously reducing from Q_{max} to 0 were also performed.

This second method of measurement allows finding the size of hysteresis in courses of characteristics. At the same time, ambient temperature and humidity were recorded during the measurement.

3. RESULTS AND DISCUSSION

The measured values of pressure, flow and temperature of fluid were transferred from the measuring unit HMG 3000 through PC to the HMGWIN3000 software for their processing. Figure 4 illustrates the course of record before and after the hydraulic control valve of pressures *p1*, *p2*, flow of hydraulic control valve *Q* and fluid temperature ϑ in dependence on time using the HMGWIN3000 software. It was performed to measure the way P→A in position 1, for increasing the flow and backwards (Fig. 2).

The course of parameters according to Fig. 4 shows higher frequencies that are unsuitable for evaluation. The HMGWIN3000 software allows filtering of higher frequency by simply pulling of roller-blind for measuring by the sensor, which is shown in Fig. 5. The filtered courses of parameters can be seen on the relevant variable in Fig. 4 with other filtered courses.

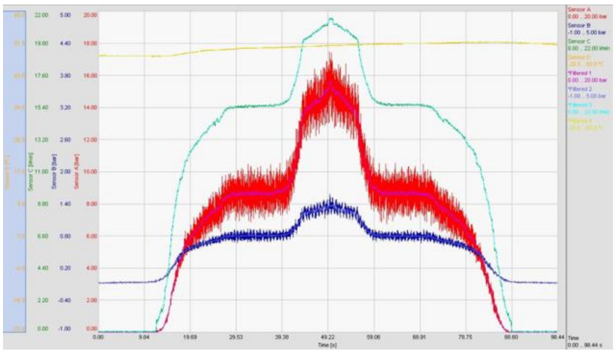
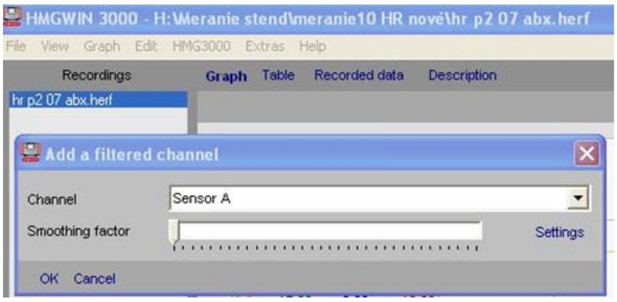


Fig. 4. Record of courses of restrictor parameters, way 1 (P→A), with increase and decrease of flow.

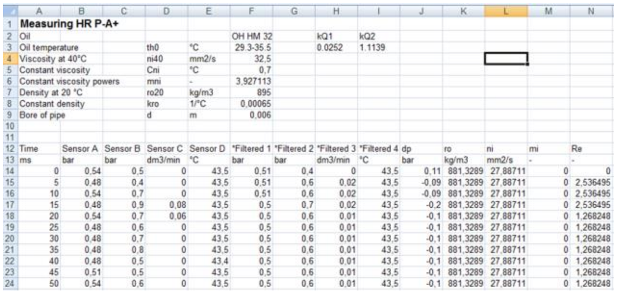


Channel: Sensor A

Smoothing factor

Fig. 5. Filtration of higher frequency by HMGWIN3000 software, with pulling of roller-blind for values of selected sensor.

In the following procedure, it is possible to convert the original courses and filtered courses of parameters into a text document *.txt using the HMGWIN3000 software. For the following processing, this document is opened in Excel, see Fig. 6.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	**Measuring HR P-A+**													
2	Oil					OH HM 32		kQ1	kQ2					
3	Oil temperature			th0	°C	29.3-35.5		0.0252	1.1139					
4	Viscosity at 40°C			ni40	mm2/s	32,5								
5	Constant viscosity			Cni	°C	0,7								
6	Constant viscosity powers			mni	-	3,927113								
7	Density at 20 °C			ro20	kg/m3	895								
8	Constant density			kro	1/°C	0,00065								
9	Bore of pipe			d	m	0,006								
10														
11														
12	Time	Sensor A	Sensor B	Sensor C	Sensor D	*Filtered 1	*Filtered 2	*Filtered 3	*Filtered 4	dp	ro	ni	mi	Re
13	ms	bar	bar	dm3/min	°C	bar	bar	dm3/min	°C	bar	kg/m3	mm2/s	-	-
14	0	0,54	0,5	0	43,5	0,51	0,4	0	43,5	0,11	881,3289	27,88711	0	0
15	5	0,48	0,4	0	43,5	0,51	0,6	0,02	43,5	-0,09	881,3289	27,88711	0	2,536495
16	10	0,54	0,7	0	43,5	0,51	0,6	0,02	43,5	-0,09	881,3289	27,88711	0	2,536495
17	15	0,48	0,9	0,08	43,5	0,5	0,7	0,02	43,5	-0,2	881,3289	27,88711	0	2,536495
18	20	0,54	0,7	0,06	43,5	0,5	0,6	0,01	43,5	-0,1	881,3289	27,88711	0	1,268248
19	25	0,48	0,6	0	43,5	0,5	0,6	0,01	43,5	-0,1	881,3289	27,88711	0	1,268248
20	30	0,48	0,7	0	43,5	0,5	0,6	0,01	43,5	-0,1	881,3289	27,88711	0	1,268248
21	35	0,48	0,8	0	43,5	0,5	0,6	0,01	43,5	-0,1	881,3289	27,88711	0	1,268248
22	40	0,48	0,5	0	43,4	0,5	0,6	0,01	43,5	-0,1	881,3289	27,88711	0	1,268248
23	45	0,51	0,5	0	43,5	0,5	0,6	0,01	43,5	-0,1	881,3289	27,88711	0	1,268248
24	50	0,54	0,6	0	43,5	0,5	0,6	0,01	43,5	-0,1	881,3289	27,88711	0	1,268248

Fig. 6. View of transferred data from files of HMGWIN3000 into Excel.

The value of pressure drop is calculated according to Eq. 1:

$$\Delta p = p_1 - p_2 \tag{1}$$

An analogical calculated was according to works published by [7-9]. These works have not dealt by the flow coefficient dependent on the temperature and viscosity. These works were used to determine of the flow coefficient. For all repeated measurements, the dependence of pressure drop Δp on flow Q for the ways P→A and P→B is shown in figures. Figure 7 shows the dependence for the way P→A towards the increase and decrease of flow, indicating that there is some hysteresis.

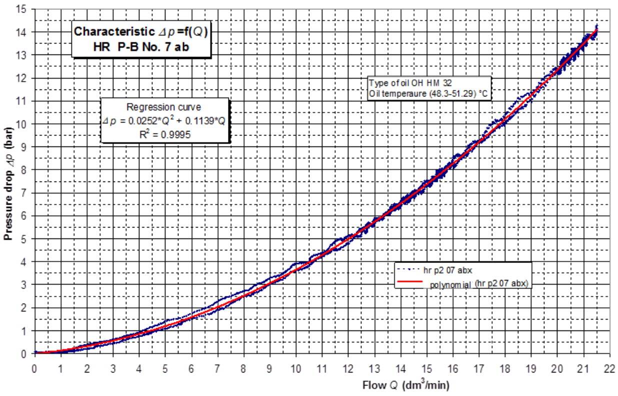


Fig. 7. Pressure drop as a function of flow of the hydraulic control valve for the way P→A towards the increase and decrease of flow.

The course was illustrated by quadratic relationship (red line) in the formula:

$$\Delta p = k_{Q1} \cdot Q^2 + k_{Q2} \cdot Q = 0.0252 \cdot Q^2 + 0.1139 \cdot Q \tag{2}$$

with quadratic coefficient of regression R^2 = 0.9995. For all measurements, all regression coefficients were very high.

In the next phase, individual measurements were transformed into relationships and their parabolic regression was performed. Figure 8 shows the courses of measurements for the P→A way towards the increase and decrease of flow.

The course of pressure drop Δp in dependence on flow Q for two measurements and for the P→A and P→B ways of hydraulic control valves HR is shown in Fig. 8 (dot-and-dashed line, dotted line and dashed line). The difference of measured values is very small.

This way it may be obtained of characteristic Δp = f(Q) for different types of hydraulic oil and for different of temperatures. This methodology allows to calculate of the characteristics Δp = f(Q) of the various elements according to ISO 8217 at

50 ° C [10]. Based on our experience be designed of hydraulic components, this methodology significantly helps in designing hydraulic components under various operating conditions.

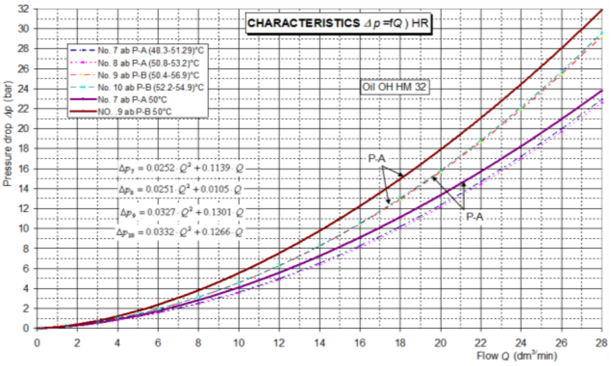


Fig. 8. Pressure drop as a flow function of hydraulic control valve HR for the P→A way (two times) and for the P→B way (two times); solid lines are for the fluid OH HN 32 at the fluid temperature 50 °C.

The flow coefficient μ of the hydraulic control valve for individual ways and measurement was calculated according to Eq. 3:

$$\mu = \frac{4 \cdot Q}{\pi \cdot d^2 \cdot \sqrt{\frac{2}{\rho} \cdot \Delta p}} \tag{3}$$

for the diameter of hydraulic control valve d = 6 mm and fluid density ρ.

Because the temperature and viscosity of OH HM 32 varied during the measurement, the following values were read from the catalogue:

- fluid density at 20 °C, $\rho_{20} = 895$ kg·m^{-3};
- coefficient of fluid density change with temperature, $k_\rho = 0.00065$ °C^{-1};
- kinematic viscosity at 40 °C, $\upsilon_{40} = 46$ mm^2·s^{-1};
- kinematic viscosity at 100 °C, $\upsilon_{100} = 6.5$ mm^2·s^{-1};
- fluid constant, $C = 0.7$ mm^2·s^{-1};
- fluid viscosity exponent, $m = 3.801203$.

Temperature of fluid ϑ was changing during the measurement; therefore, fluid density ρ was recalculated according to Eq. 4:

$$\rho = \rho_{20} \cdot \left[1 - k_\rho \cdot (\vartheta - 20)\right] = 895 \cdot \left[1 - 0.0065 \cdot (\vartheta - 20)\right] \tag{4}$$

where: k_ρ – coefficient of density change with temperature ϑ.

Similarly, also kinematic viscosity υ changes with temperature ϑ according to approximated dependence:

$$\nu = \left[(\nu_{40} + C)^{\left(\frac{40+273.15}{\vartheta+273.15}\right)^m} - C \right] = \left[(46 + 0.7)^{\left(\frac{40+273.15}{\vartheta+273.15}\right)^m} - 0.7 \right] \cdot 10^{-6}. \tag{5}$$

where: the value C for mineral oils was $C = 0.7$ according to Eq. 1.

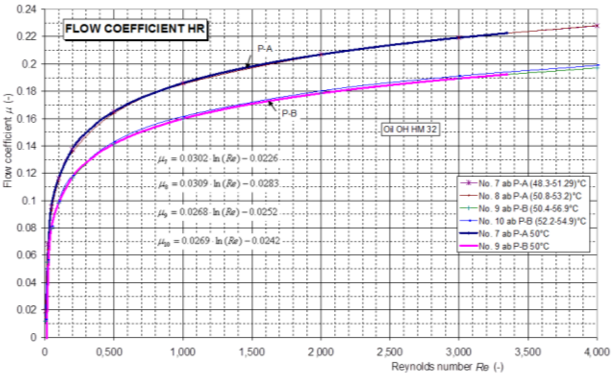


Fig. 9. Course of the flow coefficient of hydraulic control valve for the ways P→A and P→B for all measurements.

Flow coefficient for individual values was calculated using Eqs 2 and 5 according to Eq. 6:

$$\mu = \frac{4 \cdot Q}{\pi \cdot 0.006^2 \cdot \sqrt{\frac{2}{\rho} \cdot \left(k_{Q1} \cdot Q^2 + k_{Q2} \cdot Q\right)}} \tag{6}$$

for flow $Q > 0$.

Also the Reynolds number was calculated for individual values according to Eq. 7:

$$Re = \frac{4 \cdot Q}{\pi \cdot d \cdot \nu} = \frac{4 \cdot Q}{\pi \cdot 0.006 \cdot \nu} \tag{7}$$

Figure 8 shows the courses of flow coefficient μ as a function of Reynolds number Re for two measurements and ways of the hydraulic control valve P→A and P→B. The courses of individual measurements were approximated by a function with natural logarithm, with quadratic regression coefficient higher than $R^2 = 0.9942$. The regression function is given for individual measurements and ways in Fig. 8 according to Eq. 8:

$$\mu = k_{\mu 1} \cdot \ln(Re) - k_{\mu 2} \tag{8}$$

where: $k_{\mu 1}$, $k_{\mu 2}$ – regression function coefficients of flow coefficient. Their values are shown in Fig. 8.

The characteristics *Δp* = f(*Q*) of specific hydraulic resistances to movement are suitable to be given for a specific hydraulic fluid and its temperature, most often ϑ = 50 °C (Oil temperature is given by ISO standard or by the designer in the analysis of hydraulic circuit) [11,12]. The conversion of this dependence for the temperature ϑ = 50 °C, for fluid viscosity υ_{50} (calculated from Eq. 5) is performed based on modified Eq. 3 in the form *Δp* = f(*Q*):

$$\Delta p = \frac{8 \cdot Q^2 \cdot \rho_{50}}{\pi^2 \cdot d^4 \cdot \left[k_{\mu 1} \cdot \ln(Re) - k_{\mu 2}\right]^2} \tag{9}$$

where: Reynolds number can be determined from modified Eq. 7.

$$\mathrm{Re} = \frac{4 \cdot Q}{\pi \cdot d \cdot \nu_{50}} \tag{10}$$

The relationship *Δp* = f(*Q*) for the fluid OH HM 32, temperature 50 °C, and way P→A and P→B of the measured hydraulic control valve is shown in Fig. 9 (thick lines). There can be seen a difference in characteristics *Δp* = f(*Q*) for measurements under different temperatures. By using Eqs 4,5,9,10, we can describe the said characteristic under different fluid temperatures. It is important to obtain the dependence of the flow coefficient of specific hydraulic control valve and its specific way according to Eq. 8.

4. CONCLUSION

The paper presents the methodology for measurements of static characteristics *Δp* = f(*Q*) of hydraulic resistances to movement. These characteristics can be measured for different types of fluid and under different temperatures. On the basis of these results, the method allows recalculating the relationship *Δp* = f(*Q*) for other types of fluid and for other temperatures.

The methodology is presented on the example of measuring these characteristics on the hydraulic control valve and with the specific measuring chain. According to this methodology, for practical purposes, it is possible to recalculate the relationship *Δp* = f(*Q*) also on the basis of catalogue data from the manufacturer of relevant components (according to Fig. 1).

It is also possible to recalculate these characteristics for biodegradable fluids if we obtain the characteristics, for example for mineral oil-based fluids, by authors [13,14].

This methodology allows to use of the characteristics Δp = f(Q) when designing new elements under various operating conditions (different temperatures and different type of oil).

Acknowledgement

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