IMPACT OF INPUT PARAMETERS ON THE FLOW EFFICIENCY OF HYDROGENERATORS

Daniel SKLADANÝ[1], Zdenko TKÁČ[2], Michal SKLADANÝ[3], Ján KOSIBA[4]

[1,2,3,4] Department of Transport and Handling, Slovak university of Agriculture, Nitra

Abstract
This article presents tests of axial piston hydraulic pump running in various operational modes. Finding an optimal combination of operational pressure, revolutions per minute and temperature of oil in order to achieve maximal possible flow efficiency was the aim of this study. The impact of change of parameters on change of flow efficiency was statistically computed, so this work is a contribution for practical tasks, when optimal and most economical setting of device is demanded.

Key words: *axial piston hydraulic pump; volumetric efficiency; oil temperature; hydrostatic pressure.*

INTRODUCTION
Modern day´s demand on environmental protection leads our department to looking for energy saving solutions in every aspect of technology, hydraulics including. Hydraulic pumps and motors have many leakage paths from high pressure to low pressure, so a significant amount of energy is lost to leakage. This loss is known as the volumetric loss *(Grandall 2010)*. Hydraulic transducers operate the most efficiently in certain range of revolutions per minute, known as nominal rpm. This operational rate is connected to higher fluid flow, and this can cause more cavitation and friction in pipes. In some cases, inner leak in hydraulic pump is higher than losses in pipes, or vice versa. According Lan (2022) among all types of pumps, the axial piston pump is widely used owing to its high efficiency, and capability of variable displacement. For this purpose, axial piston hydraulic pump will be tested, to determine optimal combination of temperature and pressure of oil in hydraulic circuit, to establish highest efficiency possible. Michalides (2023) points out, that the individual properties of hydraulic fluids are mainly affected by temperature and pressure. While pressure forces oil to fall behind in imperfectly fitting areas of hydraulic pump, increased temperature, thus change of viscosity, makes oil leak through these areas faster. Koralewski (2011) reminds that all those losses are also a function of current motor operating parameters and of the oil viscosity changing during the system operation. Since Stawinski (2022) already started this topic with small gear hydraulic pumps, we will focus only on piston hydraulic pump of higher geometric volume. This and similar types of piston hydraulic pumps are widely used in agriculture, forestry, construction and aerospace industry, *(Ernst 2021)* so results will help to find optimal solution for everyday use.
Goal of this research was to establish which of monitored parameters (pressure, temperature) has the highest impact on change of volumetric efficiency. Side task is to find out, whether inner leak will be higher than resistance in pipes, similar to experiment of Stawinski (2022).

MATERIALS AND METHODS
For this test, we used axial piston hydraulic pump and electric drive with following parameters:
Tab. 1. Axial piston pump parameters:

Type of hydraulic pump	Max geometric volume [dm^3]	Nominal rpm [min^{-1}]	Max pressure [MPa]
Axial piston pump	0.22	1500	25

Drive unit consisting of *11kW* electric motor and *11kW* frequency converter was used. Using frequency converter, we can consider operational speed as precisely set with minimal deviation from real value. This parameter is extremely important for our experiment – it is the only parameter set to precise value. Heating up was done by choking the flow of the fluid, as in *figure 1*, that means, pressure cannot be set to exact value. Choke valve is set by hand with feedback from measurement unit. However, pressures in hydraulic circuits fluctuate within small interval, thus it is not possible to set wanted value without any deviation. The same stands for temperature, it is hard to set, because of multiple variables during experiment like increasing ambient temperature, different choking intensities, different operational speeds… To eliminate these small deviations of pressures and temperatures, we will use analysis of variance to take these deviations into account.

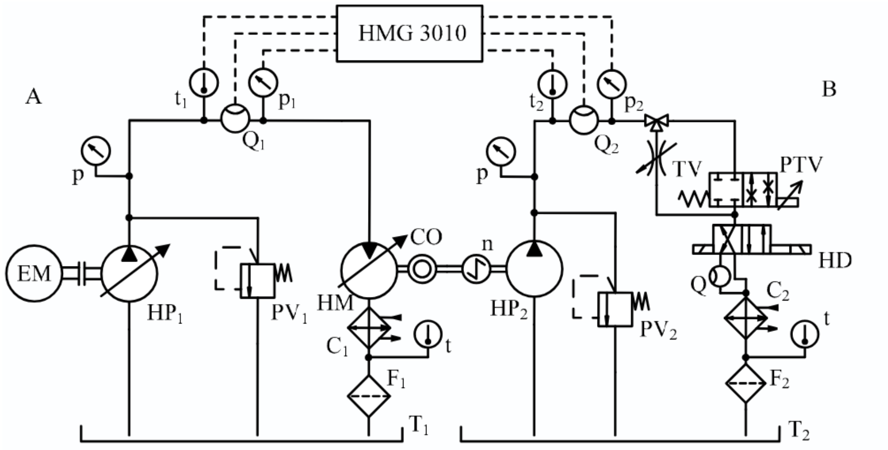

Fig. 1. Hydraulic scheme of testing device according Kosiba (2023) , where: *A* – primary circuit; *B* – secondary circuit; *EM* – electric motor; *HP1* – regulating hydraulic pump; *HP2* – non-regulating hydraulic pump; *HM* – hydraulic motor; *F1*, *F2* – filter; *T1*, *T2* – tank; *C1*, *C2* – cooler; *CO* – coupler; *TV* – throttle valve; *PTV* – proportional throttle valve; *p* – pressure sensor; *t* – temperature sensor; *Q* – flow rate sensor; *n* – speed sensor

Measuring of hydraulic parameters in circuit was done by HYDAC sensors, set to measuring interval *0,02 s* during *10 s* lasting measurements.

Tab. 2. HYDAC sensors:

Sensor	Measured parameter	Range	Unit	Accuracy
HAD 4748-h	Pressure	0 – 40	MPa	±0.25 % MR
EVS 3108-H	Flow	6 – 60	$dm^3 \cdot min^{-1}$	≤ 2 % RV
ETS 4148-H	Temperature	-25 – 100	°C	±0.4 % MR

**MR – measuring range, RV – Real value*

For safety purposes we choose to run experiment with lower operating speeds, up to *1000* min^{-1}, and pressures up to *10 MPa*. *0 MPa* were not considered, because according Koralewski (2013) at very low pressures, volumetric losses tend to be close to 0. Hydraulic pump was set to maximal geometric volume, *0.22* $dm^3 \cdot s^{-1}$. Our coolers set another limit, in terms of temperature, because it is recommended that they should not exceed *60°C*. Hydraulic circuit was filled with hydraulic oil MOL farm NH Ultra, made of mineral oils. This type of hydraulic fluids is not likely to degrade over time, or when exposed to excessive heat, meaning conditions during all measurements will be the same.

Experiment itself was carried out accordingly: We set temperature of hydraulic oil the same as ambient temperature *(23°C)* and we measured hydraulic flow in our device set to *500* min^{-1} and *2.5 MPa*. We were increasing pressure by *2.5 MPa* up to *10 MPa*. After recording flows in all pressure modes, we increased operating speed to *750* min^{-1} and run the same pressures again. The same for *1000* min^{-1}. Having all combinations at ambient temperature, we increased oil´s temperature by choking up to *30°C* and carried out the same combinations of pressures and operating speed. Temperature was being increased up until *60°C*, by *10°C* gaps, according to *Tab. 3*.

Tab. 3. Scheme of measurements:

		Operating speed [min⁻¹]											
		500				750				1000			
No.	T [°C]	Pressure [MPa]											
1.	23	2.5	5	7.5	10	2.5	5	7.5	10	2.5	5	7.5	10

2.	30	2.5	5	7.5	10	2.5	5	7.5	10	2.5	5	7.5	10
3.	40	2.5	5	7.5	10	2.5	5	7.5	10	2.5	5	7.5	10
4.	50	2.5	5	7.5	10	2.5	5	7.5	10	2.5	5	7.5	10
5.	60	2.5	5	7.5	10	2.5	5	7.5	10	2.5	5	7.5	10

Every parameter was measured for 10 seconds, meaning we had 500 values and used their arithmetic mean.

Volumetric efficiency was computed form geometric volume, operating speed and measured, real flow, by formula (1), Tkáč (2021):

$$\eta_q = \frac{Q_r}{Q_t} \cdot 100 = \frac{Q_r}{V_g \cdot n} \cdot 100$$

(Chyba! V dokumentu není žádný text v zadaném stylu.)

Where: η_q is volumetric efficiency (%), Q_r is real (measured) flow ($m^3 \cdot s^{-1}$), Q_t is theoretical flow ($m^3 \cdot s^{-1}$), V_g is geometric volume (dm^3), n is revolutions per second (s^{-1}).

For statistical approach, ANOVA method was used. This method can tell us which of the parameters had the biggest impact on volumetric efficiency. To create graphs, we used Matlab software.

RESULTS AND DISCUSSION

Following graphs represent computed volumetric efficiency from real measured flows. Form all of them, we can observe increase in efficiency with higher temperatures. This result is counterintuitive, we predicted, that higher temperature causing lower viscosity will cause inner leak of fluid in hydraulic pump and this way, it will reduce efficiency. Apparently, easier flow in pipes caused by lower viscosity is much bigger factor and it beats inner leaks, causing overall system to behave more effectively.

This result is also in contradiction with Stawinski (2022), they found out that flow efficiency is supposed to decrease with higher temperature. Possible explanation is, that piston hydraulic pumps are generally tighter, reducing more of possible inner leak, unlike in gear pumps, where fluid can be falling behind around teeth, or around side plane, as described in Guo (2020). Main source of the leakage in piston pumps is whether the slipper-swash plate or the barrel-port plate, producing over 94% of the total leakage *(Bergada 2012).*

Efficiency lowers with increasing pressure, this result was expected, because higher pressure in the system means, there is more pressure in the pump as well and any minor leak in pump will cause more fluid falling behind. Kapsiz (2022) confirms this phenomenon in his work.

Another observation from these three graphs is that with increasing operational rate, fluid efficiency increases. This result is intuitive as well, we all know, that hydraulic pumps operate most efficiently at their nominal rpm, in this case *1500 min^{-1}*. The closer we get, the bigger flow efficiency will be.

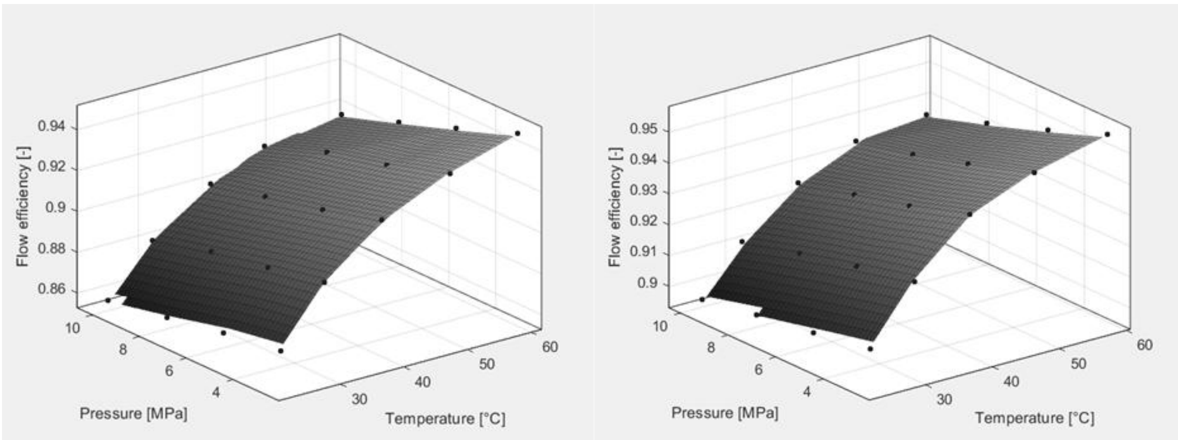

Fig. 1,2. Graph of flow efficiency with respect to pressure and temperature, at 500 min^{-1} and 750 min^{-1}

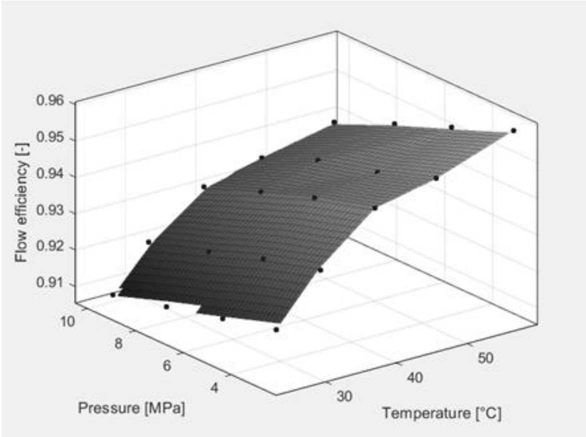

Fig. 3. Graph of flow efficiency with respect to pressure and temperature, at 1000 min^{-1}.

Statistical takes on this problem led us to the results, that temperature had the biggest impact on flow efficiency. This is shown by the ANOVA method. Since we have every flow rate computed as arithmetic mean of 500 values, we did not have to check normal distribution.

First, we took average temperatures, pressures and flows for every operational rate, having these three tables: (Because they were not exactly set).

Tab. Chyba! V dokumentu není žádný text v zadaném stylu.. Measured flows with respect to Pressure and temperatures at 500 min^{-1}:

	t [°C]				
	22.5911	29.6292	38.5216	48.4568	59.6421
p [MPa]	Q [$dm^3 \cdot min^{-1}$]				
2.5051	9.6047	9.9038	10.1503	10.3151	10.4228
5.0024	9.5577	9.8427	10.0656	10.2163	10.3031
7.5140	9.4899	9.7768	9.9890	10.1363	10.1957
10.0359	9.4301	9.6938	9.9180	10.0141	10.0924

Tab. 5. Measured flows with respect to Pressure and temperatures at 750 min^{-1}:

	t [°C]				
	23.8625	30.2273	38.6392	47.6698	58.8185
p [MPa]	Q [$dm^3 \cdot min^{-1}$]				
2.5130	14.9661	15.2649	15.5336	15.6719	15.7649
5.0511	14.9054	15.1948	15.4316	15.5603	15.6467
7.4944	14.8499	15.1191	15.3507	15.4719	15.5332
9.9477	14.7853	15.0307	15.2665	15.4000	15.4292

Tab. 6. Measured flows with respect to Pressure and temperatures at 1000 min^{-1}:

	t [°C]				
	25.3600	31.0403	38.9446	47.3067	58.1393
p [MPa]	Q [$dm^{-3} \cdot min^{-1}$]				
2.5730	20.2633	20.5621	20.8377	20.9185	21.0820
5.0290	20.1686	20.4626	20.7312	20.7957	20.9318
7.4486	20.0701	20.3437	20.6084	20.6979	20.7948
9.9760	19.9751	20.2243	20.4676	20.5473	20.6299

From those we got ANOVA table for every operational rate:

Tab. 7. Anova table for 500 min^{-1}

Variation source	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Rows	0.1717	3	0.0572	74.1489	$5.15 \cdot 10^{-8}$	3.4903

Columns	1.4107	4	0.3527	456.9254	$5.36 \cdot 10^{-13}$	3.2592
Error	0.0093	12	0.0008			
Overall	1.5917	19				

Tab. 8. Anova table for 750 min^{-1}

Variation source	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Rows	0.1836	3	0.0612	94.1331	$1.32 \cdot 10^{-8}$	3.4903
Columns	1.3880	4	0.3470	533.7636	$2.12 \cdot 10^{-13}$	3.2592
Error	0.0078	12	0.0007			
Overall	1.5793	19				

Tab. 9. Anova table for 1000 min^{-1}

Variation source	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Rows	0.3645	3	0.1215	185.3312	$2.58 \cdot 10^{-10}$	3.4903
Columns	1.4107	4	0.3527	537.9514	$2.03 \cdot 10^{-13}$	3.2592
Error	0.0079	12	0.0007			
Overall	1.7831	19				

From percentual ratios of sum of squares we got idea about each of parameter´s contribution to the overall change of efficiency. This is shown in graph on *fig. 4*. *F* values are in all cases much bigger than *F critical value*, that means differences between groups are statistically remarkable. *P* value is almost 0, and this indicates, that differences were not random.

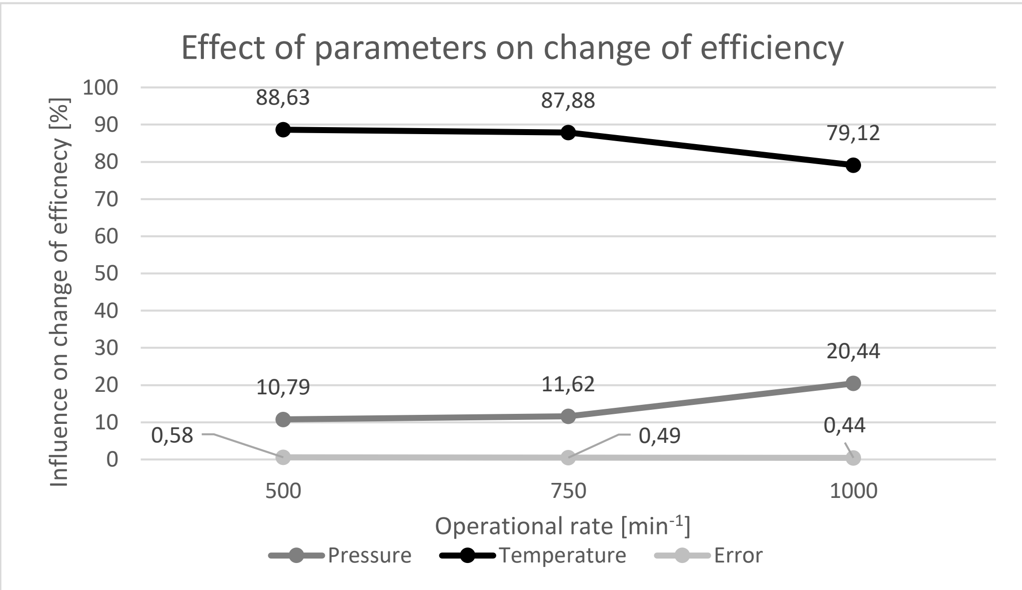

Fig. 4. Effect of parameters on change of efficiency

CONCLUSIONS

The effect of change of observed parameters on flow efficiency was determined. Temperature of oil and its change in viscosity has a much bigger impact on flow efficiency than high pressure in hydraulic circuit. For the sake of as economical operation as possible, we recommend using lower pressures at nominal rpm with oil heated up to maximal temperature, that manufacturers prescribe. Another interesting take was, that in hydraulic piston pumps, inner leak is not as big concern, as in hydraulic gear pumps. This led us to the conclusion that it is more economical to run piston pumps with oil heated up to higher temperatures, compared to gear pumps.

ACKNOWLEDGMENT
This study was supported by Visegrad Grants no. 52410187.

REFERENCES

1. BERGADA, J. M., et al. (2012) A complete analysis of axial piston pump leakage and output flow ripples. *Applied mathematical modelling*, 36.4: 1731-1751.
2. ERNST, Meike; VACCA, Andrea. (2021) Hydrostatic vs. hydrodynamic components of fluid pressure in the tribological interfaces of axial piston machines. *Tribology International*, 157: 106878.
3. GRANDALL, David Rossing. (2010) The performance and efficiency of hydraulic pumps and motors. *PhD Thesis*. University of Minnesota.
4. GUO, Rui, et al. (2020) Research on identification method of wear degradation of external gear pump based on flow field analysis. *Sensors,* 20.14: 4058.
5. KAPSIZ, Murat. (2022) The efficiency of mobile hydraulic system with diesel engine and axial piston pump analysis. *Journal of Engineering Research*, 10.4B.
6. KORALEWSKI, Jan. (2011) Influence of hydraulic oil viscosity on the volumetric losses in a variable capacity piston pump. *Polish Maritime Research*, 55-65.
7. KORALEWSKI, Jan. (2013) Influence of viscosity and compressibility of aerated oil on determination of volumetric losses in a variable capacity piston pump. *Polish Maritime Research*, 4: 3-17.
8. KOSIBA, Ján, et al. (2023) Testing of Regulating and Non-Regulating Hydraulic Pumps *Acta Technologica Agriculturae*, vol. 26, no. 4, Slovak University of Agriculture in Nitra, pp. 231-237.
9. LAN, Yuan, et al. (2022) Experimental investigation on cavitation and cavitation detection of axial piston pump based on MLP-Mixer. *Measurement*, 200: 111582.
10. MICHALIDES, M., Čorňák, Š., Jelínek, J., Janoušková, R., Hujo, Ľ. & Nosian, J. (2023). Degradation of Ecological Energy Carriers Under Cyclic Pressure Loading. *Acta Technologica Agriculturae*, *26*(3), 2023. 173-179.
11. STAWIŃSKI, Łukasz, et al. (2022) Investigation of the influence of hydraulic oil temperature on the variable-speed pump performance. *Eksploatacja i Niezawodność,* 24.2: 289-296.
12. TKÁČ, Z., et al. (2021) Investigation of degradation of ecological hydraulic fluid. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science,* 235.24: 7925-7933.

Corresponding author:
Ing. Daniel Skladaný, Institute of Agricultural Engineering, Transport and Bioenergetics, Faculty of Engineering, Slovak University of Agriculture Nitra, Trieda Andreja Hlinku 2, 949 76 Nitra, Slovak Republic, phone: 0948 041 352, e-mail: xskladany@uniag.sk