23rd International Conference
ENGINEERING MECHANICS 2017
Svratka, Czech Republic, 15 – 18 May 2017

THE ADVANTAGES OF A NEW HYDRAULIC CYLINDER DESIGN WITH A CONTROL SYSTEM

T. Siwulski[*], U. Warzyńska[**]

Abstract: *In the paper, a new design of a hydraulic cylinder is presented and some of its advantages in comparison to a standard hydraulic cylinder design are discussed. The mathematical comparative analysis of standard and a new cylinder design, including analytical and numerical approach is shown. A new cylinder design is characterized by a better heat dissipation, improved fluid circulation in cylinder chambers and higher stiffness of a system.*

Keywords: Hydraulic cylinder, Heat dissipation, Bulk modulus.

1. Introduction

An extensive use of hydraulic systems in drives of machines and devices results directly from the advantages of this type of drive, such as high power to weight ratio and modular design. However, the disadvantages of hydraulic systems, such as changing fluid properties with temperature and high demands on its purity make the operation of hydraulic systems hindered because of increased degradation of system components in harsh environmental conditions, occurring eg. in mines, steel mills and processing plants. The research on the causes of hydraulic machines failures operated in underground copper ore mines, made by the authors and other research teams (Król et al., 2009) indicate that the most common elements prone to wear are hydraulic cylinders. Described in this article a new design of hydraulic cylinder has some certain advantages, including among others, better exchange of heat and increased stiffness of a system.

2. Theoretical analysis

Thermal energy

Classic hydraulic cylinders with power supply lines form a system wherein fluid cannot exchange completely in the cylinder chambers, and thus the ability to dissipate thermal energy stored in the actuator and to remove contaminants out of the system is significantly limited (Fig. 1). Research carried out by the authors (Siwulski and Warzyńska, 2017) indicate that temperature of fluid in classic hydraulic cylinders operating with great intensity in the environment characterized by high temperature and dust, greatly exceeds the permissible value of operation. The relationship describing the hydro-mechanical efficiency of a cylinder η_{hmc}, which for hydraulic cylinders is taken as the total efficiency η_c, takes into account the power losses occurring in the piston sealing ΔN_{f1}, the gland sealing ΔN_{f2} and hydraulic losses associated with flow resistance ΔN_h and for the extension stroke of a piston takes the form:

$$\eta_c = \frac{F \cdot v - \Delta N_{f1} - \Delta N_{f2} - \Delta N_h}{Q \cdot p} \quad (1)$$

[*] Tomasz Siwulski, PhD. Eng.: Wroclaw University of Science and Technology, Faculty of Mechanical Engineering, Department of Maintenance and Operation of Logistics, Transportation and Hydraulic Systems, PL, tomasz.siwulski@pwr.edu.pl

[**] Urszula Warzyńska, MSc. Eng.: Wroclaw University of Science and Technology, Faculty of Mechanical Engineering, Department of Maintenance and Operation of Logistics, Transportation and Hydraulic Systems, PL, urszula.warzynska@pwr.edu.pl

The above analysis indicates that the efficiency of hydraulic cylinders mainly depends on the amount of energy dissipated in the piston and gland sealing. Therefore, maintenance of a high sealing efficiency during the whole operation time is essential to its proper operation.

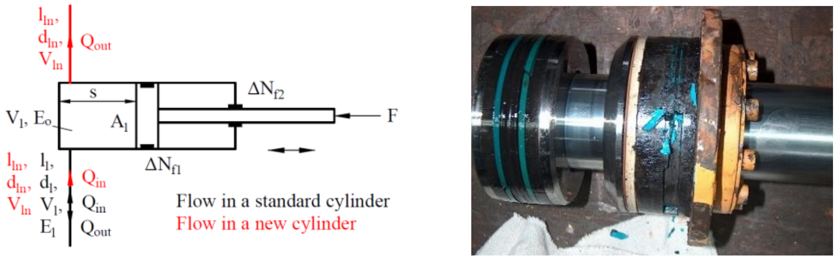

Fig. 1: Scheme of double-acting cylinder and an example of a degraded sealing.

The power loss in sealing is a function of the technical parameters of sealing and guide elements (related to the type of material) and also surface which cooperate with the sealing elements or any impurities. As a source of thermal energy can be regarded mechanical losses at sealing nodes, hydraulic losses, and in some cases external influence, eg. heat source (diesel engine). The possibility to remove heat from a cylinder is enabled only through returning of fluid to a tank or a cooler and through the radiating to the environment. However, in the case of machines operating in high ambient temperature, the possibility of emitting heat to the environment is limited. The construction of a hydraulic cylinder itself also prevents the complete replacement of the fluid contained in the chambers. The volume *Vc* of fluid to be discharged into the supply line during the movement is proportional to stroke *s* and piston area A_1 (or piston minus rod area, A_2). Thus, the volume *Vo* of fluid discharged from the cylinder (V_c) and then from a supply line (V_l) is:

$$V_o = \begin{cases} 0 \; for \; V_l \geq V_c \\ V_c - V_l \; for \; V_l < V_c \end{cases} \tag{2}$$

It is reasonable, therefore, to formulate a claim that during operation of a cylinder, a certain volume of the fluid never will be released to the tank, and upon using long and relatively large diameter supply lines in combination with a relatively small cylinder diameter and small stroke, the effect of no circulation of fluid outside the region of cylinder and a supply line will take place.

Stiffness of the system

Another important aspect is the stiffness of a system: cylinder – power supply line. This issue is particularly important in hydraulic drives of booms and operating arms, from which is required to achieve significant accuracy and position constancy of a tool over operating time (e.g. drilling machines, cranes, etc.). The most used applications cylinders are permanently connected to the hydraulic supply lines, creating a system whose rigidity is significantly affected by hydraulic lines stiffness (Hružík et al., 2013; Burrows and Edge, 2002). The displacement of cylinder piston with rigid non-deformable walls and excluding friction in the seals may be described by the equation:

$$\Delta s_c = \frac{s \cdot \Delta p}{E_o} \tag{3}$$

where: Δs_c – change of cylinder stroke as a result of fluid compressibility, s – fluid column height in a cylinder chamber, Δp – pressure difference between pressure in a cylinder chamber and pressure outside the system, E_o – fluid bulk modulus (oil).

While the displacement of a piston including power supply line takes the form of:

$$\Delta s_{cl} = \frac{\Delta V_o + \Delta V_l}{\frac{\pi \cdot D^2}{4}} = \frac{\frac{\pi \cdot (s \cdot D^2 + l \cdot d^2) \cdot \Delta p}{4 \cdot E_o} + \frac{\pi \cdot l \cdot d^2 \cdot \Delta p}{4 \cdot E_l}}{\frac{\pi * D^2}{4}} = \frac{\Delta p}{D^2} \cdot \left(\frac{s \cdot D^2 + l \cdot d^2}{E_o} + \frac{l \cdot d^2}{E_l} \right) \tag{4}$$

where: Δs_{cl} – change of cylinder stroke as a result of fluid compressibility and hydraulic line (hose) elasticity, l – length of a supply line, d – internal diameter of a supply line, E_l – bulk modulus of a supply line.

Effective bulk modulus of a system including compressibility of fluid and elasticity of a hose is equal to:

$$E_{ol} = \frac{s \cdot D^2 + l \cdot d^2}{\frac{s \cdot D^2 + l \cdot d^2}{E_o} + \frac{l \cdot d^2}{E_l}} \tag{5}$$

3. A new design of a hydraulic cylinder

The results of fluid flow analysis and the theoretical system stiffness analysis, which were briefly presented above, clearly indicated that it is reasonable to provide a solution which allows the improved circulation of fluid in the system, while limiting the impact of the supply line on system stiffness. Based on these assumptions an innovative hydraulic system was developed that allows exchange of fluid in the cylinder chambers, part of which is specially made hydraulic cylinder (Fig. 2). A description of the invention may be found in (Siwulski and Radziwanowska, 2016).

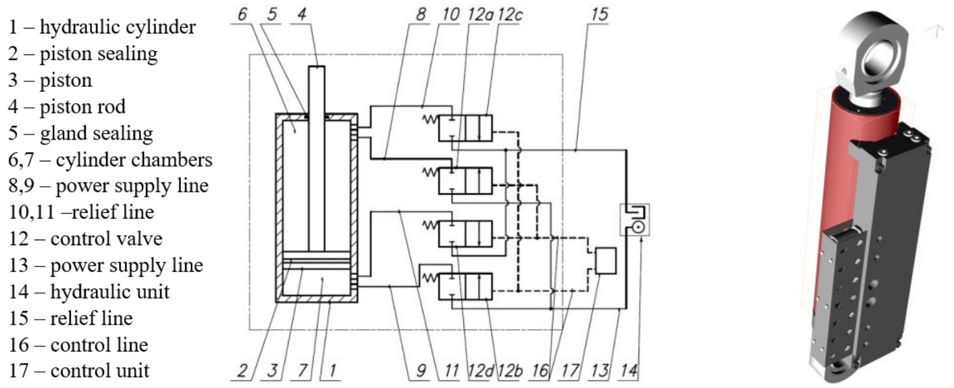

Fig. 2: A schematic diagram of a new design of hydraulic cylinder with a control system and a model of prototype hydraulic cylinder.

A comparative mathematical analysis was performed for the standard design of a cylinder with two different power supply line lengths (l = 2000 mm and l = 500 mm) supplying fluid power to a bottom chamber and the new design of a cylinder (supply line length l_n = 100 mm). According to the new idea, the control valves are mounted on a cylinder in order to limit the impact of effective bulk modulus in cylinder supply lines when the cylinder is blocked. Assuming for the standard cylinder bulk modulus for oil equal to E_o = 1500 MPa (Yang et al., 2016), and bulk modulus for hydraulic line (hose) E_l = 400 MPa (Burrows and Edge, 2002) the effective bulk modulus (Eq. (5)) for the standard cylinder l = 2000 mm is equal to E_{ol} = 1009 MPa while for a standard cylinder l = 500 mm, E_{ol} = 1322 MPa. In a new cylinder design, the infinite stiffness of supply lines walls was assumed (because they are made in a block of steel) and therefore the effective bulk modulus is equal to oil bulk modulus E_o = 1500 MPa.

4. Numerical simulations results

Numerical simulations in the field of computational fluid dynamics (CFD) were done in Ansys CFX using immersed solid algorithm. The boundary condition at the inlet was mass flow rate Q = 1.5 kg/s, while at the outlet a free outflow at atmospheric pressure. The difference in temperature between the fluid in a chamber and fluid in a supply line was set at Δt_p = 40 °C. Pre-start temperature in the entire fluid domain was set at t_2 = 80 °C while the temperature of the fluid at inlet equal to t_1 = 40 °C. Piston movement function was set in the range of 50 % of the full stroke. As a result of numerical analyses, temperature distributions in the domain of fluid in the individual time steps in transient simulation were obtained. Total analysis time was equal to two cycles of the cylinder. The amount of heat discharged from the system *ΔEc* during one cycle describes the relationship:

$$\Delta E_c = E_{c2} - E_{c1} = c_w \cdot t_{sr} \cdot m_2 - c_w \cdot t_1 \cdot m_1 = C * (t_{sr} - t_1) \tag{6}$$

where C is a constant:

$$C = c_w \cdot m_2 = c_w \cdot m_1 \#\# \tag{7}$$

and c_w – specific heat of oil (constant value, independent of temperature), c_w = 1880 kJ / kg.K, m_1, m_2 – fluid mass supplied to and discharged from a system respectively, t_{sr} – average temperature of fluid flowing out of the system measured at the outlet during one cycle of cylinder operation.

To enable the comparison of results, the average temperature of fluid flowing out of the system versus time of simulation was depicted in Fig. 3 and the parameter SPOC was introduced, defined as:

$$SPOC = \frac{(t_{sr2}-t_1)-(t_{sr1}-t_1)}{\Delta t_p} \cdot 100\ \% \tag{8}$$

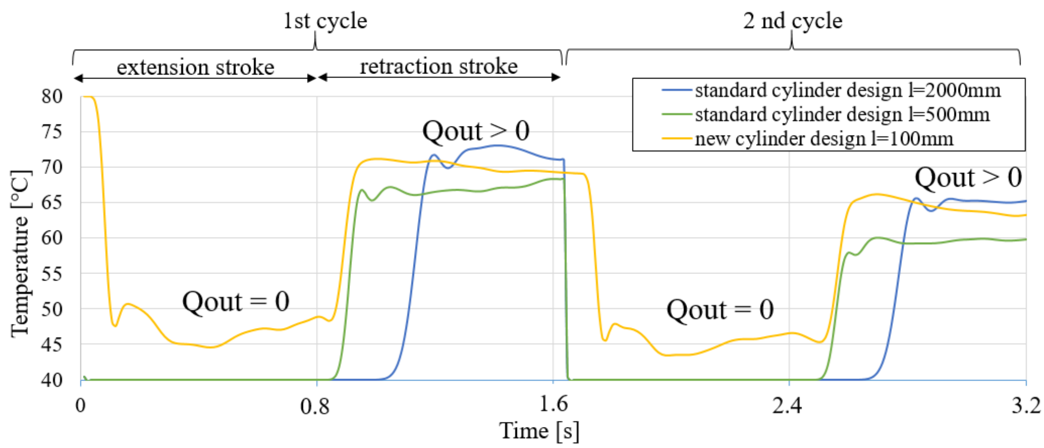

Fig. 3: The results of temperature at the outlet during the double cycle of the hydraulic cylinders.

In Tab. 1 the comparison of thermal energy dissipation (SPOC parameter) for the analyzed cylinders is shown calculated in reference to a standard cylinder design l = 2000 mm.

Tab. 1: A comparison of the cylinder designs on the basis of thermal energy dissipation.

	1st cycle			**2nd cycle**		
Hydraulic cylinder type	standard		new	standard		new
l or l_n [mm]	2000	500	100	2000	500	100
Improvement of heat dissipation (SPOC) [%]	-	10.15	20.52	-	3.39	15.55

5. Conclusions

The carried out research, undertaken development project and presented results of numerical simulations clearly indicate a significant potential of the presented solution in many areas. Its advantages, including, inter alia, indicated in this publication the possibility of significant improvement of fluid exchange in the cylinder chambers, which increases a possibility of heat energy and contamination discharge from the cylinder, and a positive effect on the rigidity of the system. Other than those mentioned positive features of the presented solution is increased safety by preventing free movement of the cylinder under load in case of supply line damage, but this aspect is the subject of a separate publication.

References

Burrows, C.R. and Edge, K.A. (2002) Power Transmission and Motion Control: PTMC 2002. Professional Engineering Publishing Ltd.

Hružík, L., Vašina, M. and Bureček A. (2013) Evaluation of bulk modulus of oil system with hydraulic line. EPJ Web of Conferences 45, 01041.

Król, R., Zimroz, R. and Stolarczyk, Ł. (2009) Failure analysis of hydraulic systems used in mining machines operating in copper ore mine KGHM POLSKA MIEDZ S.A. Scientific Papers of the Institute of Mining of the Wroclaw University of Technology, 128, pp. 127-139 (in Polish).

Siwulski, T. and Radziwanowska, U. (2016) A new design of the controlled hydraulic cylinder piston with a total fluid exchange, Patent Application No. P415174 (in Polish).

Siwulski, T. and Warzyńska, U. (2017) Hydraulic cylinder with the system supporting the exchange of fluid in the chambers. Proceedings of 30th PRMR Conference, Zakopane (in Polish).

Yang, S., Tao, A., Luo, Y., Zhang J., Zhou, P. and Zhou. L. (2016) Experimental measurements of bulk modulus for two types of hydraulic oil at pressures to 140MPa and temperatures to 180°C. 10th International Fluid Power Conference, Dresden, pp. 193-204.