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## EXPERIMENTAL INTEGRAL REGULATING PARAMETERS OF A BLADDER-TYPE HYDRAULIC ACCUMULATOR

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**Main factors influencing the regulating parameters of gas-charged hydraulic accumulators are thermodynamic processes occurring during the gas compression and expansion. Method of experimental determination of the polytropic index of gas processes in the hydraulic accumulator is improved. An experimental setup was installed for the investigation of integral regulating parameters of the bladder-type hydraulic accumulator. The parameters of non-stationary expansion of the air in the accumulator's shell during its operation with a simple short pipeline are experimentally investigated and analyzed. Polytropic index was regularly decreasing in the cycles #1 to #4 from 2.07 to 1.95. Storage volume of hydraulic accumulator, at the same time, increased on 6.0 % while discharge time decreased on 3.6 %. Obtained experimental trends are explained by the transient thermodynamic processes in the gas inside the hydraulic accumulator before the dynamic equilibrium with the external environment is established.**

**Key words:** hydraulic accumulator, non-stationary expansion, storage volume, polytropic index.

### Introduction

Hydraulic accumulators are used to maintain a constant pressure in hydraulic systems during pump switch offs and to smooth out pulsations of pressure in transient processes. Hydraulic accumulator is a device for accumulating and sequentially energy release in the form of a volume of pressurized working fluid. The use of hydraulic accumulators significantly decreases the frequency of pump switches, increasing its service period. Hydraulic accumulators are used in various fields of the engineering: in water supply and other pressure pipelines (Zhuk et al., 2016; Shi et al., 2019), hydro drive systems (Puddu & Paderi, 2013; Kumar et al., 2017; Bravo et al., 2018; Wu et al., 2019), energy engineering (Morozov et al., 2017), etc.

Gas-charged hydraulic accumulators depending of the construction are bladder-type, diaphragm-type and piston-type (Gangwar et al., 2014; Cronk & Van de Ven, 2017). Air and inert gases are used as the working gas medium in hydraulic accumulators. The principal schemes of bladder-type hydraulic accumulators are presented at Fig. 1. The peculiarity of bladder-type hydraulic accumulators in water supply is the absence of contact of water with the walls of the shell, so for these purposes the bladders have the shape of a bag and are made only from food grade material.

An important function of hydraulic accumulators are the smoothing of pressure jumps and damping of vibrations in the hydraulic system, novel achievements in this field are done by Hashim et al., 2018 and Zhao et al., 2019. The main factors influencing the regulating parameters of such hydraulic accumulator are thermodynamic processes occurring during the gas compression and expansion. Puddu & Paderi, 2013, and Wasbari et al., 2017, have analyzed the differences between the thermodynamic behaviour of real and ideal gases to determine their effect on the compression and expansion gas processes inside hydraulic accumulators, which has an impact on

accumulator's storage volume. Zhang et al., 2018, have demonstrated suitability of the Soave-Redlich-Kwong adiabatic equation for gas-loaded accumulator. Zhuk et al., 2016, performed a theoretical analysis of gas processes in the shells of bladder-type hydraulic accumulators, which are the components of automated water pumping stations. The values of generalized dimensionless storage volume factor of the hydraulic accumulator are obtained for isothermal and adiabatic processes, as well as for polytropic process with the index  $n = 1.8$ . It was shown that the minimum storage volume corresponds to polytropic gas expansion process, so this fact should be taken into account when designing pump systems with hydraulic accumulators.

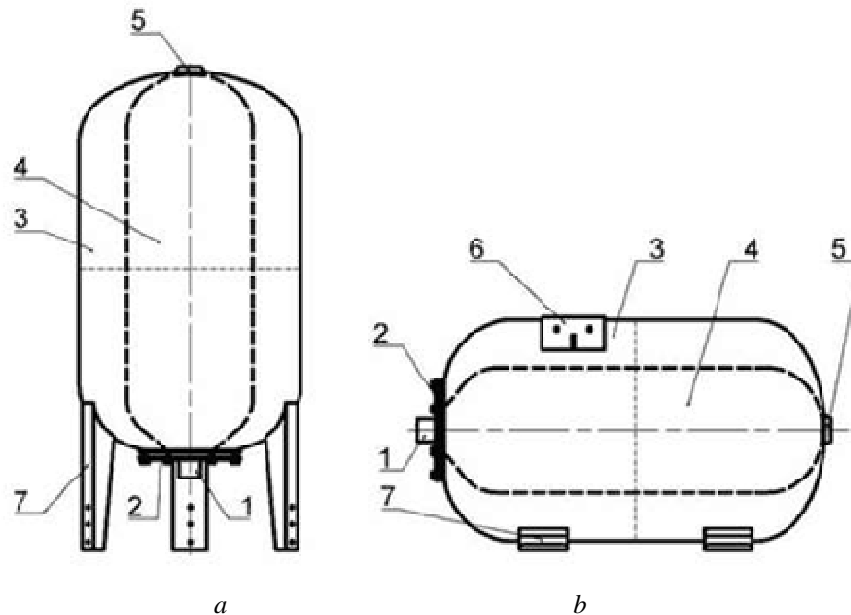


Fig. 1. Schemes of a bladder-type hydraulic accumulator:

*a* – vertical; *b* – horizontal;

1 – hydraulic cap; 2 – flange; 3 – steel shell; 4 – bladder;

5 – charging valve; 6 – mounting elements; 7 – supports

### The purpose of the study

The purpose of this study is to find experimentally gas characteristics of the non-stationary expansion of air in the shell of the bladder-type hydraulic accumulator during its operation with a simple short pipeline and to obtain the trends of the regulating parameters of the bladder-type hydraulic accumulator.

### Materials and methods

The object of the study is the process of expansion of the air in the shell of the bladder-type hydraulic accumulator. The subject of the study is the change in time of volume and absolute pressure of the air inside the accumulator during its discharge, as well as the value of the polytropic index of the corresponding gas process.

The general view of the experimental setup is shown in Fig. 2. The experimental setup consists of the vortex pump PKM60, bladder-type hydraulic accumulator with a nominal volume of  $24 \text{ dm}^3$ , as well as a set of measuring instruments and equipment. The measurement of air pressure inside the accumulator was carried out using a DC pressure transducer (error  $\pm 1.5 \%$  in the pressure range  $\leq 1.2 \text{ MPa}$ , the range of temperatures  $0\text{--}100 \text{ }^\circ\text{C}$ , the response time of the pressure

signal  $\leq 2.0$  ms), which converts the measured pressure into a unified voltage output signal. An Arduino UNO R3 based controller was used to convert the signal into digital form. The current pressure values every 0.1 s were sent to the personal computer and saved using special C++ software as txt data file.

The amount of water displaced from the hydraulic accumulator during the periods between pump operations was measured by electronic weight AXIS BDU 60 equipped with the digital interface RS-232 to transmit current values of mass to the personal computer. Maximum error of mass measurement is  $\pm 10$  g and the mass data were updated automatically every 0.125 s.

The timing of the pressure values in the accumulator and the volume of fluid flowing from the hydraulic accumulator through a short simple pipeline were performed at the moment of stopping the pump corresponding the maximum pressure in the accumulator.



Fig. 2. Experimental setup for the study of transient gas processes in the bladder-type hydraulic accumulator: 1 – pump PKM60; 2 – hydraulic accumulator with a nominal volume of  $24 \text{ dm}^3$ ; 3 – DC pressure transducer; 4 – controller based on Arduino UNO R3 board; 5 – computer

Volume of water flowed out from the hydraulic accumulator in the process of its discharge:

$$\Delta W_w(t) = \Delta M_w(t) / \rho_w, \quad (1)$$

where  $\Delta M_w(t)$  is the current mass of water flowed out from the hydraulic accumulator at time  $t$  from the beginning of its discharge;  $\rho_w$  – specific mass of water. Taking into account the low volume compressibility of water, the specific mass was taken as a function of water temperature only at any pressure in the accumulator.

## Results and discussion

A series of studies of the change in the time of the air parameters in a bladder-type accumulator with a nominal volume of  $W_{nom} = 24 \text{ dm}^3$  is performed at the experimental setup (Fig. 2). The air volume was first precharged to an excess pressure of  $p_0 = 1.5$  bar. The maximum excess pressure in the hydraulic accumulator corresponding to the switching off the pump was  $p_1 = 3.0$  bar, and the minimum system working pressure  $p_2 = 1.56$  bar. An online recording of the actual change of excess pressure in the accumulator during its charge and discharge cycles # 1 – # 4 is shown in Fig. 3.

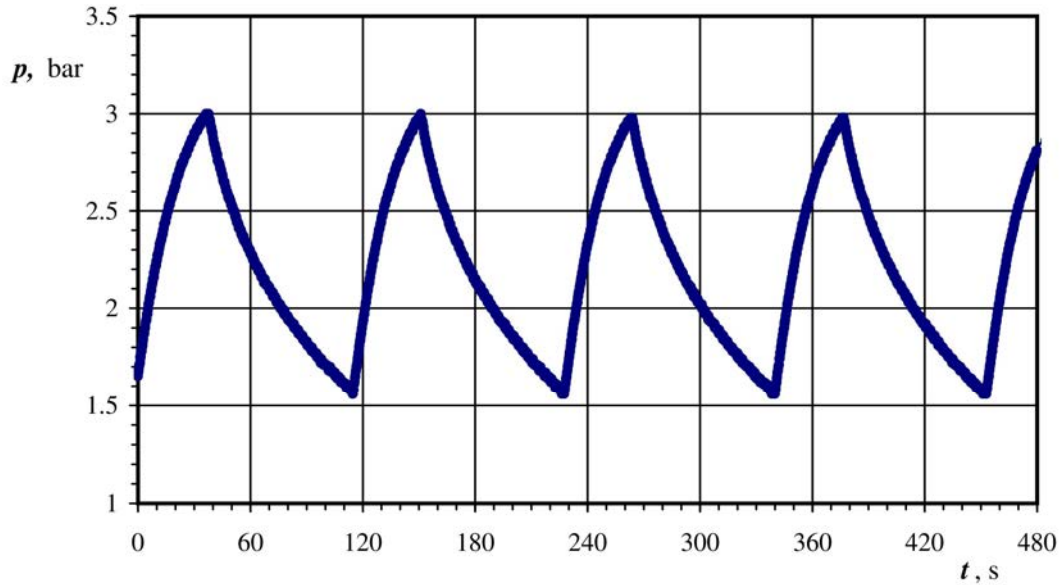


Fig. 3. Change of the excess air pressure in the bladder-type hydraulic accumulator with a nominal volume of  $W_{nom} = 24 \text{ dm}^3$  when operating with a simple short pipeline (gauge pressures in the accumulator:  $p_0 = 1.5 \text{ bar}$ ;  $p_1 = 3.0 \text{ bar}$ ;  $p_2 = 1.56 \text{ bar}$ )

Absolute pressure values were used further to calculate the parameters of the gas environment in the hydraulic accumulator. Experimental graphs of the absolute pressure in the shell of the accumulator and of the volume of water displaced from the accumulator during its discharge for the cycle # 1 are presented in Fig. 4.

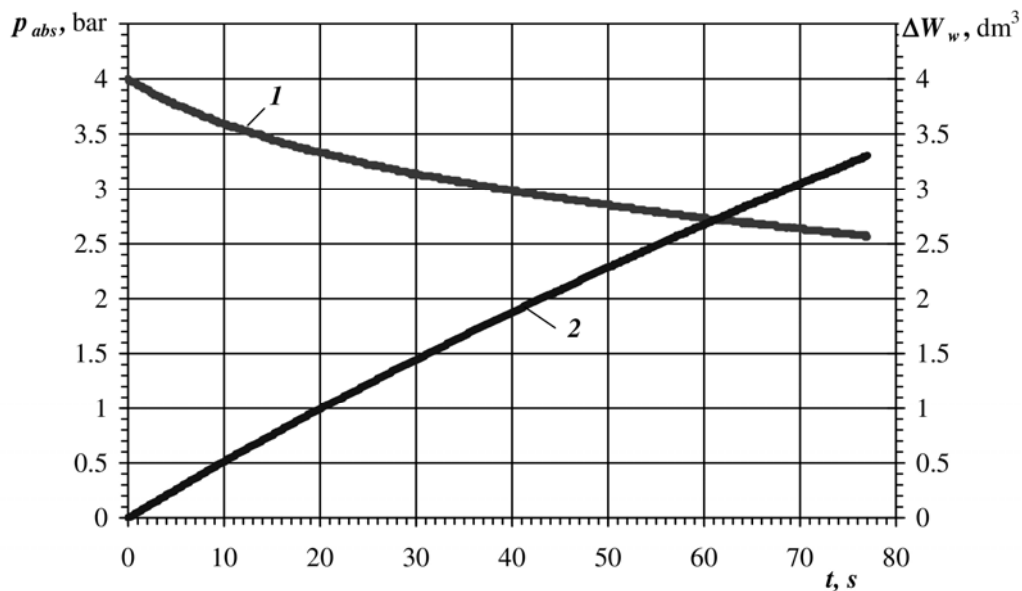


Fig. 4. Change of the absolute pressure in the hydraulic accumulator (1) and of the volume of water displaced from the accumulator (2) during its discharge (for the cycle #1)

The estimated volume of air inside the hydraulic accumulator at any moment of time is found based on the equation of material balance:

$$W_a(t) = W_{a,1} + \Delta W_w(t), \quad (2)$$

where  $W_{a,1}$  is the volume of air in the accumulator at the beginning of the discharge cycle.

The amount of air inside the accumulator at the beginning of each discharge cycle is calculated using the ideal gas equation:

$$W_{a,1} = W_{a,0} \frac{p_{abs,0}}{p_{abs,1}}, \quad (3)$$

where  $W_{a,0}$  – initial volume of air in the hydraulic accumulator after its precharging to the absolute pressure  $p_{abs,0} = 2.5$  bar;  $p_{abs,1}$  – absolute pressure of the air inside the accumulator at the beginning of the discharge cycle; for the cycles #1–#4  $p_{abs,1} = 3.98$ – $4.00$  bar.

The initial volume of air in the accumulator is found as the difference between the nominal volume of the hydraulic accumulator  $W_{nom} = 24$  dm<sup>3</sup> and the volume of the bladder  $W_b$ . The volume of the bladder, identical to the one installed in the experimental hydraulic accumulator, was measured using the method of displacement volume and found to be equal  $W_b = 0.33$  dm<sup>3</sup>; therefore, for the studied hydraulic accumulator  $W_{a,0} = 23.67$  dm<sup>3</sup>.

The experimental dependences of absolute pressure vs. time and volume vs. time were reduced to a direct dependence of the absolute air pressure in the hydraulic accumulator as the function of the air volume. Four experimental characteristics of the gas processes inside the hydraulic accumulator are obtained for the discharge cycles #1 – #4 (Fig. 5). Characteristics #1 – #4 slowly but systematically are shifted to larger air volumes each subsequent cycle.

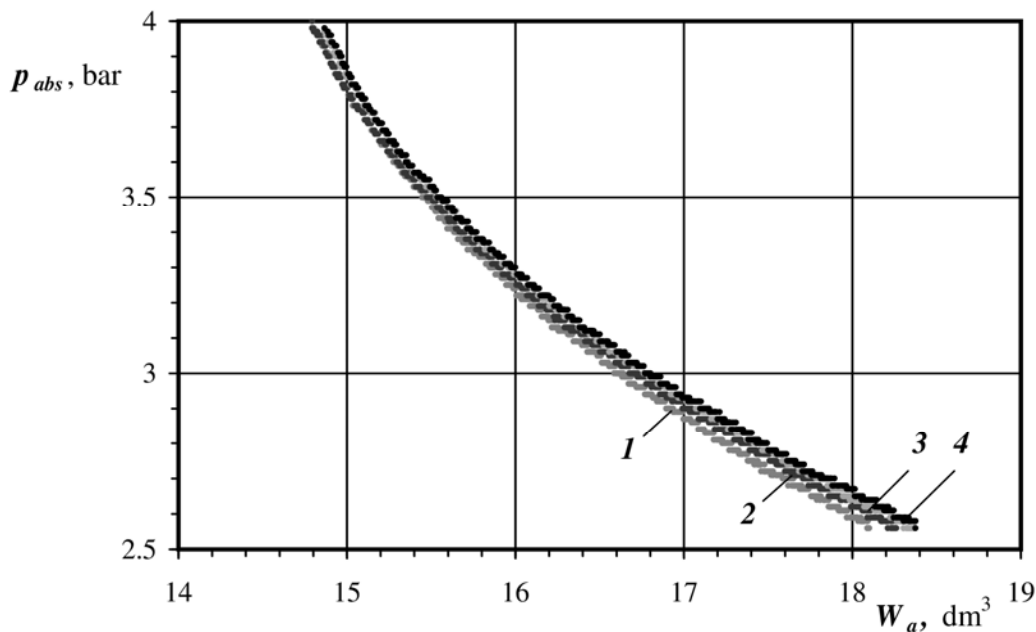


Fig. 5. Experimental gas characteristics for the process of air expansion in the bladder-type hydraulic accumulator ( $W_{a,0} = 23.67$  dm<sup>3</sup>,  $p_{abs,0} = 2.5$  bar):  
1 – 4 – discharge cycles #1 – #4 respectively

The least squares method is used to obtain approximations of results presented in Fig. 5. Experimental dependences  $p_{abs} = f(W_a)$  can be described with sufficient accuracy by the simplest power law function

$$p_{abs} = C / W_a^n, \quad (4)$$

that is, in fact, the equation of the polytropic process in ideal gas, where  $C$  is the experimental constant;  $n$  is the polytropic index. Thus, for each of the discharge cycles #1 – #4, the corresponding experimental values of the polytropic index  $n$  are obtained.

Three integral regulating parameters of the hydraulic accumulator are considered: storage (regulating) volume  $W_{reg} = (W_{a.2} - W_{a.1})$ , discharge time  $t_d$  and average water flow rate  $Q_{mid} = W_{reg} / t_d$ .

Experimental parameters of air inside the hydraulic accumulator and respective values of integral regulating parameters for the four subsequent discharge processes #1 – #4 are summarized in Table 1.

Table 1

**Main experimental results of the discharge cycles #1 – #4  
of the bladder-type hydraulic accumulator**

#	$p_{abs.1}$ , bar	$p_{abs.2}$ , bar	$W_{a.1}$ , dm <sup>3</sup>	$W_{a.2}$ , dm <sup>3</sup>	$W_{reg}$ , dm <sup>3</sup>	$t_d$ , s	$Q_{mid}$ , dm <sup>3</sup> /s	$n$
1	4.00	2.56	14.794	18.100	3.306	77.1	0.0429	2.070
2	4.00	2.58	14.794	18.260	3.466	76.4	0.0454	1.983
3	3.98	2.56	14.868	18.372	3.504	76.1	0.0460	1.961
4	3.98	2.56	14.868	18.374	3.506	74.3	0.0472	1.945

Four subsequent cycles of discharge of the bladder-type hydraulic accumulator showed the systematic changes of the main integral operating parameters, namely: increase of the storage volume from 3.306 dm<sup>3</sup> to 3.506 dm<sup>3</sup> (or 6.0 % from the value for the cycle #1), decrease of discharge time of the accumulator from 77.1 s to 74.3 s (3.6 %) and an increase of the average flow rate of water at the outlet of the hydraulic accumulator from 42.9 cm<sup>3</sup>/s to 47.2 cm<sup>3</sup>/s (10.0 %) at a constant hydraulic resistance of the regulating valve at the end of the pipeline. The polytropic index of the gas expansion processes during the discharge of the hydraulic accumulator varied from 2.07 for the cycle #1 to 1.945 for the cycle #4 (6.0 %).

The systematic changes of experimental integral regulating parameters of the bladder-type hydraulic accumulator for the four subsequent cycles of its discharge can be explained by the gradual change in the temperature mode of air inside the hydraulic accumulator at each subsequent discharge cycle. The importance of heat losses in the bladder-type hydraulic accumulators is shown in detail by Juhala et al., 2014. Preliminary analysis of thermodynamic state of air inside the hydraulic accumulator shows, that most of the operational time the calculated temperature of air inside the hydraulic accumulator is much lower comparing the temperature of water and the outside air temperature. Thus, during the first few cycles of the operation, the heat inflow to the air inside the hydraulic accumulator outweighs the heat losses, which increases the total stored energy of the air, causing an increasing in both the storage volume and the flow rate of water at the outlet of the hydraulic accumulator.

## Conclusions

1. The technique of experimental study of integral regulating parameters of the bladder-type hydraulic accumulators, as well as of the method of experimental estimation of the polytropic index for the gas processes in hydraulic accumulators, with simultaneous online measurement of pressure inside the hydraulic accumulator and of the volume of liquid, displaced from the hydraulic accumulator, are improved.

2. The experimental dependences of the absolute pressure of the air inside the bladder-type hydraulic accumulator as the function of air volume can be described with sufficient accuracy by the power law dependence (4), that is, in fact, the equation of the polytropic process in ideal gas.

3. Four subsequent cycles of discharge of the bladder-type hydraulic accumulator at a constant hydraulic resistance of the regulating valve at the end of the pipeline showed relatively small but systematic changes of the integral regulating parameters of the hydraulic accumulator: increasing of the storage volume by 6.0 % (from the cycle #1 to the cycle #4), decreasing of the discharge time by 3.6 % and increasing the average flow rate of water at the outlet of the hydraulic accumulator by 10.0 %.

4. A systematic decrease of the gas process polytropic index value from 2.07 for the cycle #1 to 1.945 for the cycle #4 is obtained for each subsequent discharge cycle. Obtained systematic changes are explained by the transient thermodynamic processes in air inside the hydraulic accumulator before the dynamic equilibrium with the external environment is established.

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## **ЕКСПЕРИМЕНТАЛЬНІ ІНТЕГРАЛЬНІ РЕГУЛЮВАЛЬНІ ПАРАМЕТРИ ГІДРОАКУМУЛЯТОРА МЕМБРАННОГО ТИПУ**

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Застосування гідроаккумуляторів значно зменшує частоту включень насосів, суттєво збільшуючи ресурс їх роботи. Основними факторами, що впливають на регулювальні параметри гідроаккумуляторів, є характеристики газових процесів, що відбуваються під час стиснення та розширення газового середовища.

Удосконалено методику експериментального визначення інтегральних регулювальних характеристик гідроаккумулятора мембранного типу, а також експериментального визначення показника політропи газових процесів в гідроаккумуляторі шляхом одночасного визначення в режимі онлайн зміни тиску повітря в гідроаккумуляторі та об'єму витісненої з гідроаккумулятора рідини. Виготовлено стенд для експериментального дослідження перехідних газових процесів у баці гідроаккумулятора мембранного типу.

Експериментальні залежності абсолютного тиску повітря в гідроаккумуляторі від його об'єму з достатньою для практики точністю можуть бути описані найпростішими степеневими залежностями, тобто описані за моделлю ідеального газу. Для чотирьох послідовних циклів розрядки дослідного гідроаккумулятора за незмінного ступеня відкриття запірно-регулювального пристрою на виході трубопроводу отримано відносно незначні, але систематичні зміни інтегральних регулювальних характеристик гідроаккумулятора, а саме: збільшення регулювального об'єму на 6,0 % (від циклу № 1 до циклу № 4), зменшення часу розрядки гідроаккумулятора на 3,6 % та збільшення середньої об'ємної витрати води на виході з гідроаккумулятора на 10,0 %. Отримано систематичне зменшення для кожного наступного циклу розрядки значення показника політропи газового процесу від 2,07 для циклу № 1 до 1,945 для циклу № 4. Отримані систематичні зміни пояснено наявністю перехідних термодинамічних процесів у газовому середовищі гідроаккумулятора до встановлення динамічної рівноваги із зовнішнім середовищем.

**Ключові слова:** гідроаккумулятор, нестационарне розширення, регулювальний об'єм, показник політропи.