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EXPERIMENTAL REGULATING PARAMETERS OF BLADDER-TYPE HYDRAULIC ACCUMULATOR

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Experimental regulating parameters of the non-stationary expansion of air inside a bladder-type hydraulic accumulator, working with the simple short pipeline, are presented in the paper. The technique of continuous online monitoring of changes in time of volume and absolute air pressure inside the hydraulic accumulator during the discharge process has been improved. Three series of experimental studies of transient gas processes inside the accumulator at different values of the average volume flow rate are made. Tendencies of change of the integral parameters of the hydraulic accumulator are obtained and analyzed depending on the serial number of the discharge cycle. A general dependence of dimensionless storage volume K_{reg} on the polytropic index n in series # 1–3, approximated by single power-law dependence, is obtained. The systematic changes of integral parameters in each subsequent discharge cycle can be explained by the non-stationary transient thermodynamic processes in air inside the accumulator until the thermodynamic equilibrium with the ambient air parameters is reached.

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

1. Introduction

Hydraulic accumulators are often used in different hydraulic systems to smooth out the fluctuations of pressure in the pipeline at transient processes during pump starts and switch offs. A hydraulic accumulator is a device for storing and sequentially releasing of energy of compressed working gas. Using hydraulic accumulators is useful due to the shortage of the number of pump switches, thus providing the increasing of its service life. Hydraulic accumulators are widely used in engineering: in water supply and other fluid pressure systems (Shi *et al.* [1]; Zhuk *et al.* [2]), in the power engineering (Morozov *et al.* [3]), in hydro-drives (Bravo *et al.* [4]; Kumar *et al.* [5]; Puddu and Paderi, [6]; Wu *et al.* [7]), etc. Parameters of transitional gas processes have a significant impact on the efficiency of the relevant engineering systems (Juhala *et al.* [8]; Mamčic and Bogdevičius, [9]).

There are bladder-type, diaphragm-type and piston-type gas-charged hydraulic accumulators (Cronk and Van de Ven, [10]; Gangwar *et al.* [11]). In these hydraulic accumulators air and some inert gases are used as working gas. An important feature of bladder-type hydraulic accumulators, used in water supply systems, is no contact of water with the walls of the chamber. Thus, bladders of water supply hydraulic accumulators are of bag-type and are made from food-grade materials.

Smoothing of pressure surges and vibration damping in hydraulic systems are studied in detail by Hashim *et al.* [12] and Zhao *et al.* [13]. Regulation of parameters of such hydraulic accumulators mainly on the thermodynamic processes, i.e. the gas compression and expansion. Puddu and Paderi, [6], and Wasbari *et al.* [14] studied the divergences of the thermodynamic parameters of real and ideal gases to find their impact on the compression and expansion of working gas, thus influencing the storage volume of hydraulic accumulator. Zhang *et al.* [15] demonstrated the applicability of the Soave-Redlich-Kwong adiabatic equation for gas-charged hydraulic accumulators. Zhuk *et al.* [2], performed a theoretical analysis of gas processes inside the bladder-type water supply hydraulic accumulators widely used in automated pumping stations. A

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comparison of dimensionless storage volumes of the hydraulic accumulator, obtained for isothermal and adiabatic conditions, as well as for polytropic process with index $n = 1.8$, shows that the minimum values of the storage volume are obtained during the polytropic process.

The purpose of this research is experimental investigation of the main regulating parameters of the bladder-type water supply hydraulic accumulator by means of analysis of transient gas process of the non-stationary expansion of air inside the hydraulic accumulator during its discharge through a short simple pipeline.

2. Materials and methods

The object of the study is the process of expansion of air inside a typical water supply bladder-type hydraulic accumulator. The subject of the study is the change in time of volume and absolute pressure of air inside the accumulator during the discharge process, as well as the values of the regulating volume and polytropic index of the corresponding gas process.

An experimental study on the change in time of air parameters in a bladder-type accumulator with a nominal volume of $W_{nom} = 24dm^3$ was performed at the experimental setup (Fig.1). It consists of the vortex pump PKM-60 (3), bladder-type hydraulic accumulator 4 with a nominal volume of $24dm^3$, as well as suction and delivery pipelines, hydraulic equipment and measuring instruments. Main parameters of the pump PKM-60 are as follows: $Q = 0.08 - 0.58dm^3 / s; H = 3 - 5m; n' = 2850\ min^{-1}$, and maximum suction head $h_{s.max} = 8.0m$.

The suction PP-R pipe *2* with a non-return valve, mechanical filter and three *90*-degree bends has diameter of $32 \times 5.4mm$ and length of $3.5m$. The suction head h_s is about $2.0m$. The delivery PP-R pipeline *5* of diameter $25 \times 4.2mm$ and length is $10.60m$ has two 90° bends and one bend at 60^o. The delivery head is $4.2m$, thus the static head is about $6.2m$. A water tap *6* was used to sudden close the pressure pipeline *5* and valve *7* was used to change hydraulic resistance of the system and hence the average water flow rate through the pressure pipeline.

Online measurements of air pressure inside the hydraulic accumulator were made by a DC pressure transducer (error $\pm\ 1.5$% in the pressure range $\leq 1.2MPa$, the range of temperatures $0 - 100°C$, the response time of the pressure signal $\leq 2.0ms$), which converts the measured pressure into a unified voltage output signal. A pressure controller based on Arduino UNO R3 board was used to convert the signal into digital form. The current pressure values were automatically sent to the personal computer each $0.1s$ and saved using special C++ software as txt data file.

The working fluid in the study was clean tap water circulating in the hydraulic system, i.e. after filling the upper tank *8* water flowed back into the lower tank *1*. The water temperature in the lower tank *1* varied in the range $12 - 14^o C$.

Air temperature, measured by a dry bulb thermometer, was in the range between $15.2^o C$ in the series #2 and $16.1^o C$ in the series #*1*. Relative humidity of the air was in the range from *69.8*% to *72.3*%.

The mass of water displaced from the hydraulic accumulator through a short simple delivery pipeline *5* in the upper vessel *8* was measured by an electronic scale *9* AXIS BDU-60 equipped with the digital interface RS-232 (10) to transmit automatically every $0.125s$ the current mass values to the computer 14. A maximum absolute error of mass measurement is $\pm 0.01kg$.

The volume of water displaced from the hydraulic accumulator in the process of its discharge can be calculated:

$$\Delta W_w(t) = \Delta M_w(t) / \rho_w, \tag{2.1}$$

where $\Delta M_w(t)$ is the current mass of water which flowed out from the hydraulic accumulator at time *t* from the beginning of its discharge; ρ_w is the specific mass of water.

Taking into account the low compressibility of water, the specific mass of water was taken only as a function of temperature regardless of the pressure in the accumulator.

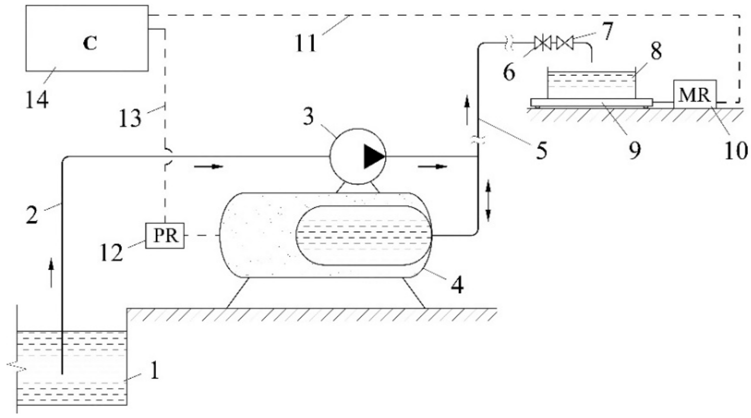

Fig.1. Scheme of the experimental setup with the bladder-type hydraulic accumulator: 1 – lower tank; 2 – suction pipe; 3 − vortex pump PKM-60; 4 − hydraulic accumulator with a nominal volume of $24dm^3$; 5 – delivery pipeline; 6 – water tap; 7 – valve; 8 – upper tank; 9 – electronic scale BDU-60; 10 – digital interface RS-232; 11, 13 – signal lines; 12 − pressure controller; 14 − computer

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

$$W_a(t) = W_{a.1} + \Delta W_w(t), \tag{2.2}$$

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

After pre-charging with air, the accumulator was not turned on for long enough time (about *1* hour), after which the pump in series was started for the first time. Thus, the initial air temperature inside the hydraulic accumulator was the same as the outside air temperature by measured a dry bulb thermometer.

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

$$W_{a.1} = W_{a.0} \frac{p_{abs.0}}{p_{abs.1}}, \tag{2.3}$$

where $W_{a.0}$ is the initial volume of air in the hydraulic accumulator after its precharging to the absolute pressure $p_{abs.0} = 2.43 - 2.49 bar$; $p_{abs.1}$ is the absolute pressure of the air inside the accumulator at the beginning of the discharge cycle; in different cycles varied in the range $p_{abs.1} = 3.76 - 3.88 bar$.

The initial volume of air in the accumulator is found as the difference between the nominal volume of the hydraulic accumulator $W_{nom} = 24dm^3$ 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 to $W_b = 0.33dm^3$; therefore, for the studied hydraulic accumulator $W_{a.0} = 23.67dm^3$.

3. Results and discussion

Three series of studies were performed at different average volumetric flow rates in the delivery pipeline. Results of online recording of the actual change of excess air pressure inside the hydraulic accumulator in series #1 − #3 are shown in Fig.2.

The hydraulic accumulator at the beginning of each series was pre-charged to an excess pressure of $p_0 = 1.46 \pm 0.03bar$. The maximum excess pressure in the hydraulic accumulator corresponding to switching off the pump was adjusted at the level $p_1 = 2.82 \pm 0.06bar$, and the minimum system working pressure $p_2 = 1.46 \pm 0.03bar$.

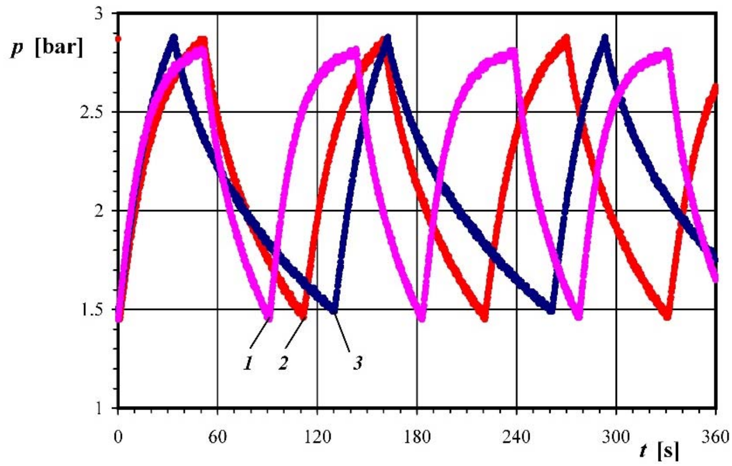

Fig.2. Variations of the excess air pressure inside the bladder-type hydraulic accumulator with a nominal volume 24dm^3 when operating with a simple short pipeline (gauge pressures: $p_0 = p_2 = 1.46 \pm 0.03bar$; $p_{1=} 2.82 \pm 0.06bar$): 1 – series #1, $Q_{mid.1} = 75.3cm^3 / s$; 2 – series #2, $Q_{mid.2} = 63.4cm^3 / s$; 3 – series #3, $Q_{mid.3} = 34.0cm^3 / s$.

The change in the duration of the charging and discharging cycles of the hydraulic accumulator for all three series is analyzed (Figs 3-5).

In all three series, regardless of the value of the average flow, the charging time decreased in each subsequent cycle, indicating the presence of transient thermodynamic processes in the first few cycles of the hydraulic accumulator after a long time in the off state. The change in the duration of the hydraulic accumulator charge t_{ch}, s, for all series is well described by linear approximations. In the series #1 at average water flow rate $Q_{mid.1} = 0.0753dm^3 / s$ an approximation dependence is obtained:

$$t_{ch} = 39.8 - 0.337N, \tag{3.1}$$

in the series #2 $\left(Q_{mid.2} = 0.0634dm^3 / s\right)$:

$$t_{ch} = 50.6 - 0.309N, \tag{3.2}$$

in the series #3 $\left(Q_{mid.3} = 0.0340dm^3 / s\right)$:

$$t_{ch} = 32.9 - 0.179N. \tag{3.3}$$

a)

b)

c)

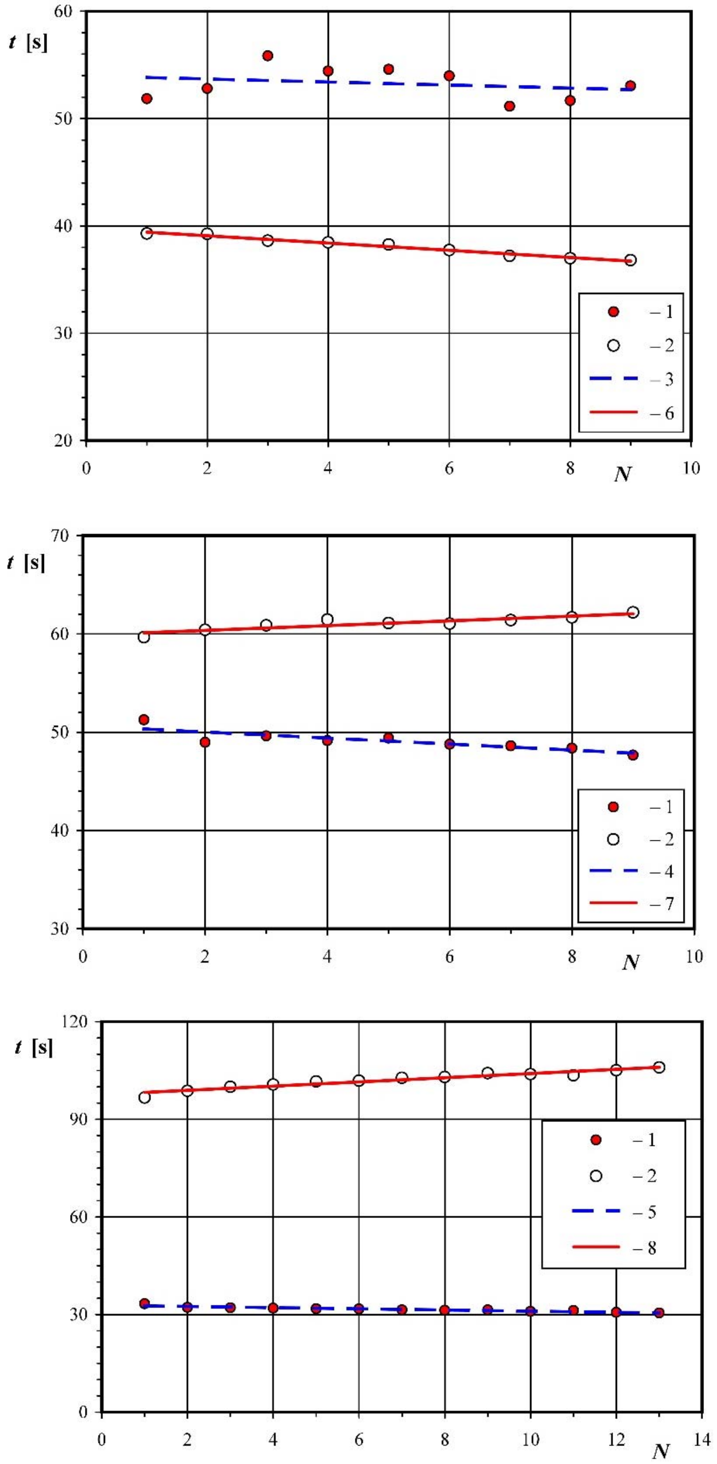

Fig.3. Charging time t_{ch} (1) and discharge time t_d (2) of the hydraulic accumulator depending on the serial number of the operating cycle: a – for series # 1, $Q_{mid.1} = 75.3cm^3/s$; b – for series # 2, $Q_{mid.2} = 63.4cm^3/s$; c – for series # 3, $Q_{mid.3} = 34.0cm^3/s$; 3-8 – linear approximations (3.1)-(3.6) respectively.

The duration of the discharge cycles of the accumulator t_d, s, showed different tendencies. In the series #1 with the highest value of the average flow rate $\left(Q_{mid.1} = 0.0753 dm^3/s\right)$ a linear decrease in the discharge time in each of the following cycles is obtained:

$$t_d = 54.0 - 0.142N, \tag{3.4}$$

whereas in the two other series, at lower values of the average flow rate, a gradual increase in the duration of the accumulator discharge time in the first few cycles of its operation is observed. In particular, for the series #2 $\left(Q_{mid.2} = 0.0634 dm^3/s\right)$:

$$t_d = 59.9 + 0.243N, \tag{3.5}$$

and for the series #3 $\left(Q_{mid.3} = 0.0340 dm^3/s\right)$:

$$t_d = 97.6 + 0.643N. \tag{3.6}$$

Absolute pressure values were used further to calculate the parameters of the gas environment through the transition processes in the hydraulic accumulator. The experimental dependences of absolute pressure vs time and volume vs time were reduced to implicit dependences of the absolute air pressure in the hydraulic accumulator as the function of the air volume. A typical experimental dependence of the absolute pressure on the volume of air in the accumulator for the discharge cycle #1.1 is presented in Fig.4.

Using the least squares method experimental dependences $p_{abs} = f\left(W_a\right)$ can be described by the simplest power law function (3.7), that is, in fact, the equation of the polytropic process in ideal gas:

$$p_{abs} = C / W_a^n, \tag{3.7}$$

where C is the experimental constant, different for each discharge cycle; n is the polytropic index.

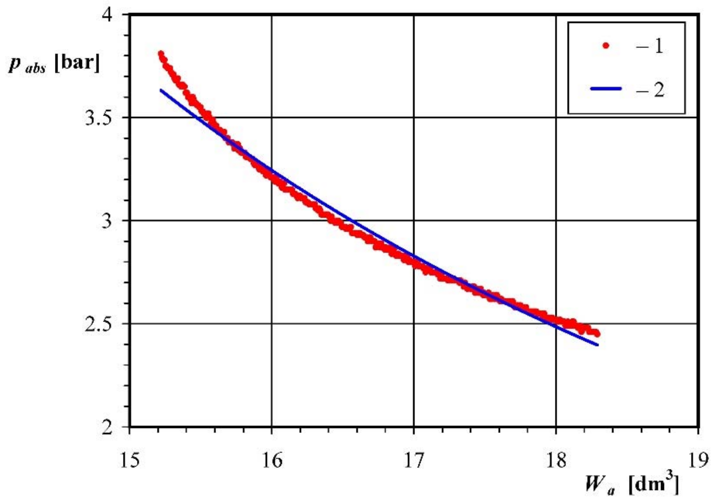

Fig.4. Experimental dependence of absolute pressure in the hydraulic accumulator and the air volume for the discharge cycle # 1.1 $\left(Q_{mid.1.1} = 78.1 cm^3/s\right)$ – 1; 2 – power law approximation by equation (3.7) with $n_{1.1} = 2.261$.

Table 1. Main experimental results of the discharge series #1-#3 of the bladder-type hydraulic accumulator.

#	$p_{abs.1}[bar]$	$p_{abs.2}[bar]$	$W_{a.1}[dm^3]$	$W_{a.2}[dm^3]$	$W_{reg}[dm^3]$	t_d, s	$Q_{mid}[dm^3/s]$	n
Series #1 $(Q_{mid.1} = 75.3cm^3/s)$								
1.1	3.81	2.45	15.221	18.291	3.070	39.285	0.0781	2.261
1.2	3.79	2.45	15.301	18.328	3.027	39.245	0.0771	2.307
1.3	3.81	2.46	15.283	18.267	2.984	38.63	0.0772	2.319
1.4	3.79	2.45	15.301	18.236	2.935	38.46	0.0763	2.358
1.5	3.79	2.45	15.301	18.193	2.892	38.265	0.0756	2.395
1.6	3.78	2.45	15.342	18.161	2.819	37.75	0.0747	2.445
1.7	3.76	2.45	15.423	18.172	2.749	37.195	0.0739	2.515
1.8	3.78	2.45	15.342	18.043	2.702	36.99	0.0730	2.549
1.9	3.76	2.43	15.297	17.937	2.639	36.815	0.0717	2.608
Series #2 $(Q_{mid.2} = 63.4cm^3/s)$								
2.1	3.85	2.48	15.493	19.422	3.929	59.655	0.0659	1.907
2.2	3.87	2.46	15.413	19.327	3.914	60.415	0.0648	1.918
2.3	3.88	2.46	15.373	19.216	3.843	60.86	0.0631	1.909
2.4	3.85	2.46	15.493	19.365	3.872	61.47	0.0630	1.932
2.5	3.87	2.48	15.413	19.321	3.908	61.115	0.0639	1.908
2.6	3.85	2.46	15.493	19.359	3.866	61.04	0.0633	1.931
2.7	3.87	2.46	15.413	19.260	3.847	61.395	0.0627	1.911
2.8	3.85	2.48	15.493	19.359	3.866	61.675	0.0627	1.901
2.9	3.87	2.45	15.413	19.231	3.818	62.195	0.0614	1.923
Series #3 ($Q_{mid.3}$=34.0cm^3/s)								
3.1	3.88	2.49	15.190	18.686	3.496	96.68	0.0362	1.988
3.2	3.85	2.49	15.309	18.740	3.432	98.745	0.0348	2.023
3.3	3.87	2.49	15.230	18.654	3.424	99.965	0.0343	2.024
3.4	3.87	2.48	15.168	18.576	3.408	100.665	0.0339	2.026
3.5	3.87	2.48	15.168	18.611	3.443	101.64	0.0339	2.011
3.6	3.85	2.48	15.247	18.694	3.446	101.835	0.0338	2.029
3.7	3.85	2.48	15.247	18.721	3.474	102.72	0.0338	2.016
3.8	3.85	2.46	15.124	18.584	3.460	102.97	0.0336	2.005
3.9	3.87	2.48	15.168	18.677	3.508	104.17	0.0337	1.979
3.10	3.88	2.48	15.129	18.627	3.498	103.87	0.0337	1.983
3.11	3.87	2.48	15.168	18.677	3.508	103.49	0.0339	1.981
3.12	3.87	2.48	15.168	18.697	3.529	105.07	0.0336	1.973
3.13	3.87	2.46	15.046	18.605	3.559	105.94	0.0336	1.953

A more detailed analysis of the dependence $p_{abs} = f(W_a)$ in Fig.4 indicates that at the beginning of the discharge cycle the actual pressure decrease is more intensive than in the approximation (3.7), and at the end of the discharge – on the contrary less. In the first 10 s of the discharge cycle #1.1, the polytropic index is 3.310, while in the last 10 s of this cycle – only 1.696, approaching the polytropic index value. Thus, the polytropic index in Eq.(3.7) when processing the whole series of data on the discharge cycle is in fact the average value of the polytropic index for this cycle. But within each cycle, the current value of the polytropic index is constantly decreasing from the beginning of the discharge of the accumulator to its end.

Using the technique described above, for each discharge cycle of the series #1-#3, the corresponding experimental mean values of the polytropic index n are obtained (Table 1).

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

With a constant degree of value opening, i.e. at a constant hydraulic resistance of the pipeline, the average volumetric flow rate Q_{mid} in all three series slowly decreased in each subsequent cycle (Fig.5). For example, in series #1 the discharge Q_{mid} decreased by 8.6% from the average value of $75.3 cm^3 / s$, while in series #2 and #3 – by 7.1% and 7.5%, respectively.

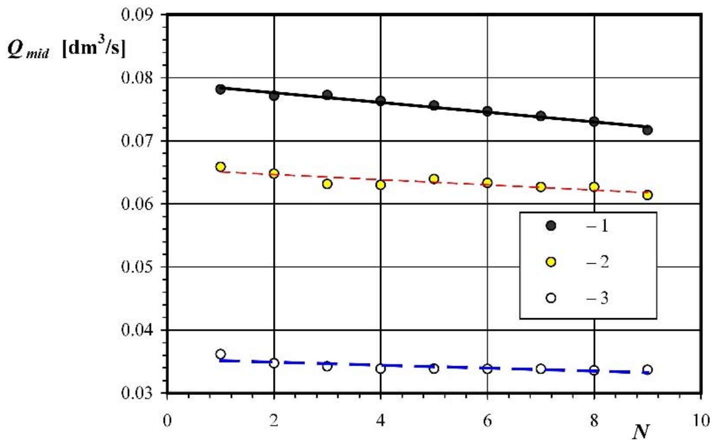

Fig.5. Mean flow rate Q_{mid} at output of the hydraulic accumulator depending on the serial number of the discharge cycle: 1 – series # 1 $\left(Q_{mid.1} = 0.0753 dm^3 / s\right)$; 2 – series # 2 $\left(Q_{mid.2} = 0.0634 dm^3 / s\right)$; 3 – series # 3 $\left(Q_{mid.3} = 0.0340 dm^3 / s\right)$.

Next linear approximations are obtained:
in the series #1 $\left(Q_{mid.1} = 0.0753 dm^3 / s\right)$:

$$Q_{mid} = 0.0792 - 0.00077 N, \tag{3.8}$$

in the series #2 $\left(Q_{mid.2} = 0.0634 dm^3 / s\right)$:

$$Q_{mid} = 0.0655 - 0.00041 N, \tag{3.9}$$

in the series #3 $\left(Q_{mid.3} = 0.0340 dm^3 / s\right)$:

$$Q_{mid} = 0.0354 - 0.00024 N. \tag{3.10}$$

To summarize the experimental results, storage volumes were reduced to dimensionless form. The dimensionless storage volume K_{reg} was defined as the ratio of the absolute value of the control volume W_{reg} and the nominal volume of the accumulator $W_{nom} = 24dm^3$. In series #1 at average flow rate $0.0753dm^3/s$ the value of K_{reg} gradually decreased from the discharge cycle #1.1 till cycle #1.9, and the total relative decrease of K_{reg} value was as high as 15.0% from the average value in the series 0.120.

In other series, at lower flow rates, there was a slight relative change in the dimensionless storage volume K_{reg}: a decrease of 2.9% in the series #2 and an increase of 1.8% in the series #3. In all experimental series the tendency to reach some constant value is obtained, and with a decrease of the average flow rate, this value occurs for a fewer number of discharge cycles.

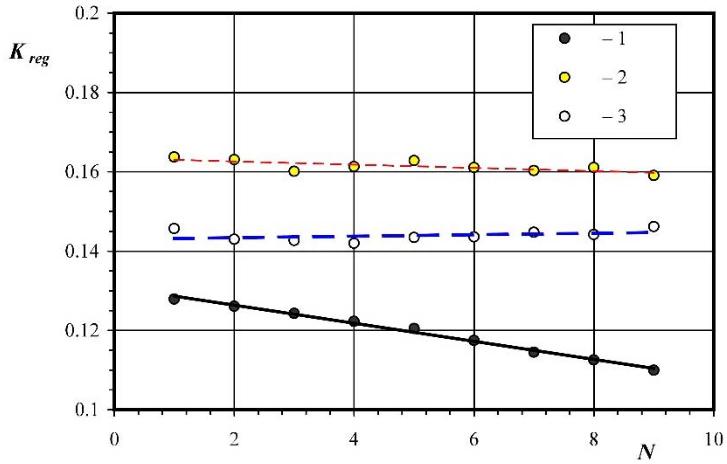

Fig.6. Dimensionless regulating volume K_{reg} of the hydraulic accumulator depending on the serial number of the discharge cycle: 1 – series # 1 $\left(Q_{mid.1} = 75.3cm^3/s\right)$; 2 – series # 2 $\left(Q_{mid.2} = 63.4cm^3/s\right)$; 3 – series # 3 $(Q_{mid.3} = 34.0cm^3/s)$.

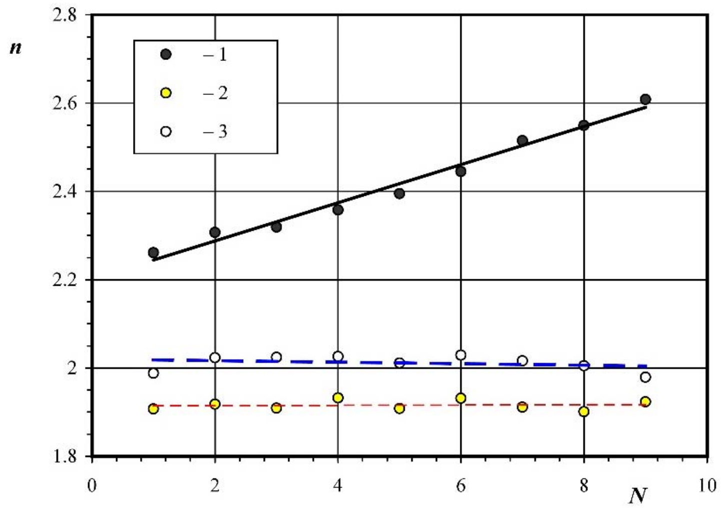

Fig.7. Mean values of the polytropic index n depending on the serial number of the discharge cycle: 1 – series # 1 $(Q_{mid.1} = 75.3cm^3/s)$; 2 – series # 2 $\left(Q_{mid.2} = 63.4cm^3/s\right)$; 3 – series # 3 $(Q_{mid.3} = 34.0cm^3/s)$.

The change of mean values of polytropic indices for all series was also analyzed. At the average volume flow rate $Q_{mid.2} = 0.0634 dm^3 / s$ and $Q_{mid.3} = 0.0340 dm^3 / s$, small differences in the values of the polytropic indices are obtained; the relative changes of the polytropic indices are equal to $+0.8\%$ and -2.9%, respectively comparing the corresponding average values (Fig.7). In the series #1, at the largest studied flow rate $Q_{mid.1} = 0.0753 dm^3 / s$, a significant increase of the polytropic index during the operation was obtained, and the relative change of the polytropic index in the series #1 is 14.4% from its average value $n_{1.mid} = 2.417$.

The influence of the average value of the polytropic index of the air expansion process in the shell of the bladder-type hydraulic accumulator on the value of the dimensionless storage volume is presented in Fig.8. The results of all three series with sufficient accuracy are approximated by a single power-law dependence:

$$K_{reg} = 0.339 n^{-1.19} . \tag{3.11}$$

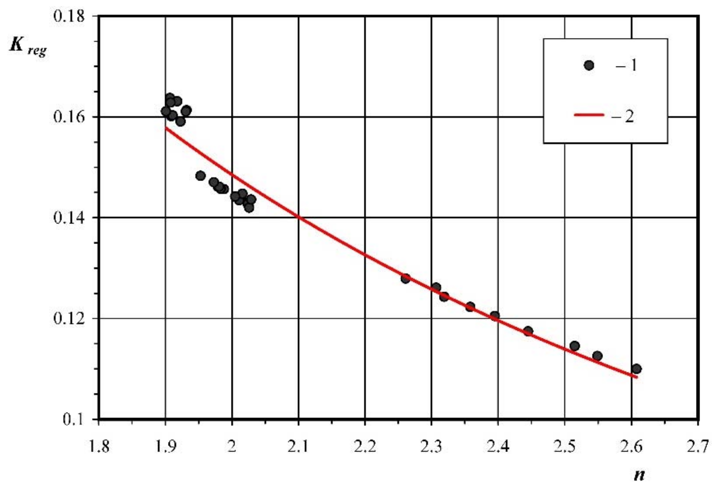

Fig.8. General dependence of the dimensionless storage volume K_{reg} and the polytropic index in series # 1–3: 1 – experimental results; 2 – power law approximation (3.11).

4. Conclusions

The main integral parameters of gas process of non-stationary expansion of air inside the bladder-type hydraulic accumulator working with the simple short pipeline are studied experimentally. The technique of continuous online monitoring of changes in time of volume and absolute air pressure inside the hydraulic accumulator during the discharge process has been improved.

Three series of experimental studies of transient gas processes inside the accumulator at different values of the average volume flow rate in the pipeline in the range from $0.0340 dm^3 / s$ to $0.0753 dm^3 / s$ are made.

The duration of each subsequent cycle of charging the accumulator in each of the three series decreased according to linear equations (3.1)-(3.3). The duration of discharge cycles in the series #1 $\left(Q_{mid.1} = 0.0753 dm^3 / s\right)$ gradually decreased according to the linear equation (3.4), while in the series # 2 $\left(Q_{mid.2} = 0.0634 dm^3 / s\right)$ and in the series # 3 $\left(Q_{mid.3} = 0.0340 dm^3 / s\right)$ – increased according to linear equations (3.5) and (3.6), respectively.

The experimental dependences of the absolute air pressure inside the accumulator on the air volume are described with sufficient accuracy by the power-law equation (3.7), which actually expresses the law of polytropic expansion of an ideal gas.

Tendencies of change of the integral parameters of the hydraulic accumulator are obtained and analyzed depending on the serial number of the discharge cycle of the hydraulic accumulator.

The mean volumetric flow rate Q_{mid} in all three series slowly decreased in each subsequent cycle: in series #1 the discharge Q_{mid} decreased by 8.6% from the corresponding average value, while in series #2 and #3 – by 7.1% and 7.5%, respectively.

A general dependence of the dimensionless storage volume K_{reg} on the polytropic index n in series # 1–3, approximated by single power-law dependence (3.11), is obtained.

The systematic changes of the integral parameters of the hydraulic accumulator in each subsequent cycle can be explained by the non-stationary thermodynamic processes of compression and expansion of air inside the accumulator until the establishment of thermodynamic equilibrium with the ambient air parameters.

Nomenclature

C	– experimental constant
$h_{s.max}$	– maximum suction head
H	– head
K_{reg}	– dimensionless storage volume
n	– polytropic index
n'	– frequency of pump impeller
N	– serial number of the operating cycle
p	– excess pressure
p_{abs}	– absolute pressure
Q	– flow rate
Q_{mid}	– average flow rate
t	– time
t_{ch}	– duration of charging
t_d	– duration of discharge
W_a	– air volume
W_b	– volume of bladder
W_{nom}	– nominal volume of hydraulic accumulator
W_{reg}	– storage (regulating) volume
ΔM_w	– current mass of water
ΔW_w	– current volume of water
ρ_w	– specific mass

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