Development and Research of an Experimental Prototype of the Positive Displacement Two-Stage Piston Hybrid Energy-Generating Machine

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Abstract. This paper considers the new principle diagram of the positive displacement two-stage piston hybrid energy-generating machine. A prototype of the two-stage piston hybrid energy-generating machine has been developed based on the analysis of working processes and frames of piston hybrid energy-generating machines, as well as by using preliminary theoretical studies. This prototype allows to visualize the movement of the liquid piston in the second stage of the machine. A set of experimental studies on a previously developed and modernized test bench made it possible to prove the working capacity of the prototype, to measure the main thermodynamic and discharge parameters, and to identify the main features of the ongoing work processes.

Keywords: piston, piston cylinder, two-stage compressor, two-stage piston hybrid energy-generating machine, liquid piston, working processes

1. Introduction

Compressors and pumps are some of the largest consumers of electricity [1, 2] and work aimed at their perfection in the field of improving efficiency, productivity and mass-dimensions parameters, will be relevant and timely in the future.

Currently, one of the main ways to increase efficiency, productivity and mass-dimensions parameters is to combine a compressor and a positive displacement pump in a single energy-generating unit [3]. The positive displacement piston hybrid machines among hybrid energy-generating units are most widely used and most of the effort has been directed to their study [4, 5, 6, 7, 8].

The realization of intensive cooling in the piston hybrid energy-generating machines (PHEM) allows to increase stage pressure ratio up to 10 [9] and, therefore, to reduce the number of stages in process of compressing gases to high pressures. For example, it is possible not to use three-stage compressors, but two-stage ones, with gas compression up to 10 MPa. This will significantly reduce the size and weight of the compressor unit.

In this paper, we consider the development and study of an experimental prototype of the positive displacement two-stage piston hybrid energy-generating machine, which is designed to compress gases to pressures of up to 10 MPa.

2. Formulation of the problem

In this section, a description of the experimental sample was carried out. The main requirements for the development of the two-stage piston compressor with a high-pressure ratio in the stage are:

– intensive cooling of the compressible gas, which allows to have the temperature of the compressible gas at the end of the compression process to be 40-50 K higher than the oil flash point [1] (it is desirable that the polytropic exponent of the terminal parameters approaches to 1);

– small clearance volume in the pump chamber and self-acting valves;

– the absence of oscillatory occurrences in the inter-stage lines and end junction pipelines;

– intensive gas cooling into inter-stage distribution pipelines in order to approach the temperature of the suction gas in the second stage closer to the temperature of the suction gas in the first stage;

– reduction or complete elimination of leakages and flows of compressible gas in piston seals and self-acting valves, especially in the second stage.

These requirements are fully met by the two-stage piston hybrid energy-generating machine (PHEM), the principle diagram of which is shown in Figure 1. The Piston strokes up during the first stage (from bottom dead-centre to top dead-centre), gas is compressed and injected in the working cavity of the first stage 3. The compressed gas from the working cavity 3 enters the decreasing space of the first stage 4 through the discharge valve of the first stage 2. Then from the decreasing space of the first stage through the inter-stage pipeline 5 enters the increasing space of the second stage 6, from where through the discharge valve of the second stage 7, enters the working cavity of the second stage 9.

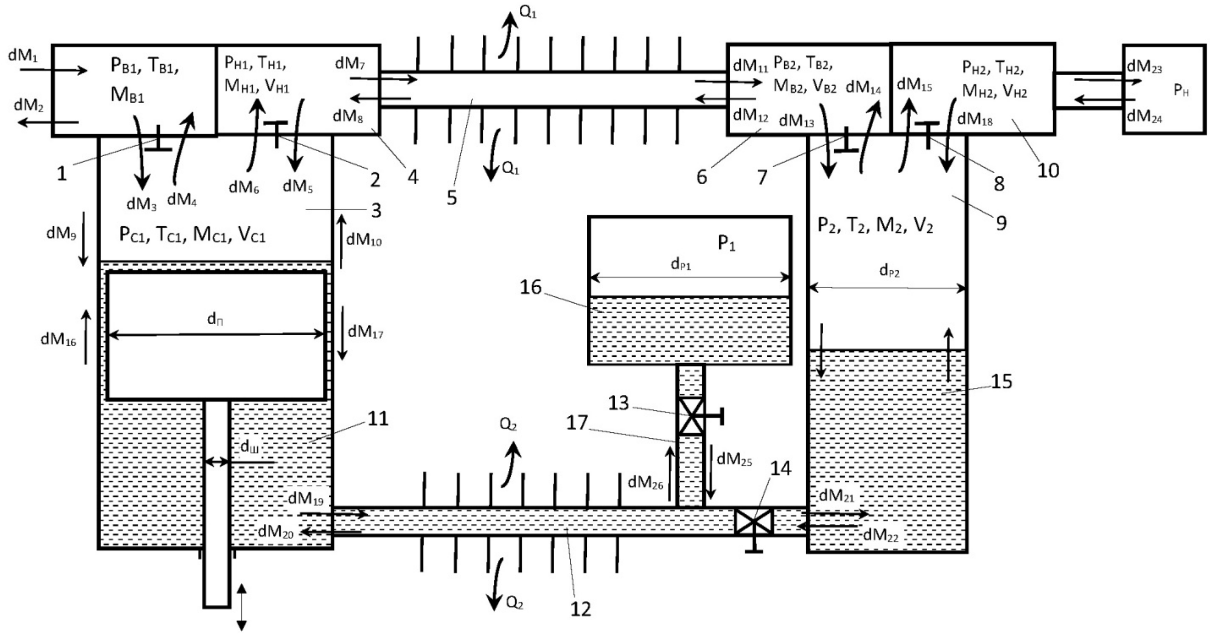

Figure 1. Principle diagram of PHEM.

Currently, the liquid from the working cavity of the second stage enters the sub-piston space of the first stage 11 through the control valve 14 and the pipe 12. In addition, the liquid also enters the sub-piston space 11 through the pipe 12 from the gas cap 16. The inter-stage connecting pipelines 5 and 12 are finned to remove the heat of gas compression and can be blown by the cooling air fan. The volume of the working chamber 3 of the first stage increases, when the first stage piston downs (from the top dead-centre to the bottom dead-centre), then the suction gas enters to the working cavity 3, through the suction valve of the first stage 1, while the discharge valve of the first stage 2 and suction valve of the second stage 7 both close. At the same time (when the piston moves downward), liquid from the sub-piston space 11 enters the working cavity of the second stage, the volume of which begins to decrease. Then the liquid enters the gas cap 16 through the pipe 12, as well as the pipe 17, control valves 13 and 14. The working cavity of the second stage is divided into the gas part 9 and the liquid part 15.

The volume of the liquid part 15 begins to increase, and the volume of the gas part 9 begins to decrease, then gas is compressed to the discharge pressure, and then it moves through the discharge valve of the second stage 8 and the discharge chamber of the second stage 10 to the gas consumer. Thus, pressure in the gas cap 16 and in the working cavity of the second stage 9 increases due to the movement of liquid from the sub-piston space during the piston of the first stage downs.

Compression of the gas in the second stage is carried out using the liquid from the sub-piston space of the first stage, i.e. liquid piston. The use of the gas cap is necessary to drain part of the excess liquid from the sub-piston space 11, because the volume of liquid that must enter the working cavity of the second stage to

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compress the gas is significantly less than the volume of the liquid which is pushed from the sub-piston space. This excess liquid drains into the gas cap.

In this case, it is necessary to select such fluid resistances of the liquid line which is going to the gas cap and to the second stage in order to provide the necessary liquid amount entering the second stage, and its excess to the gas cap. This issue is partially considered in [10]. Fluid resistances of these lines are regulated by the valves 13 and 14. A patent application is filed for this principle diagram [11].

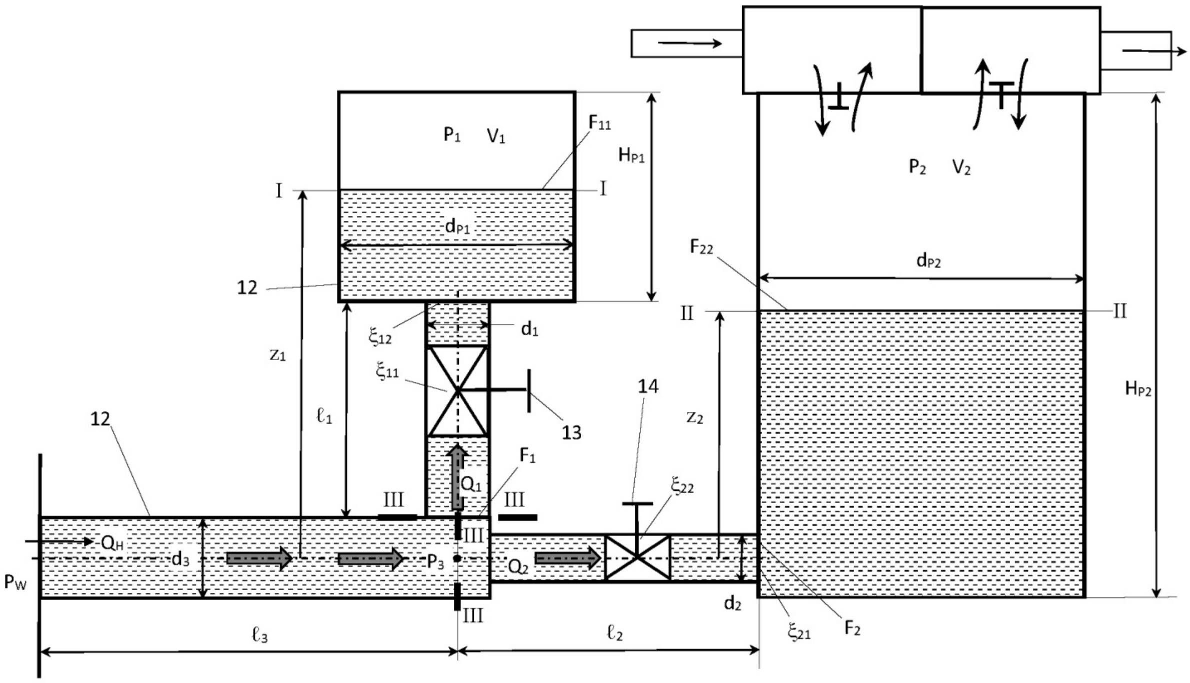

Figure 2. Principle diagram of PHEM.

The developed experimental prototype had the main characteristics in table 1 (Fig. 1 and Fig. 2).

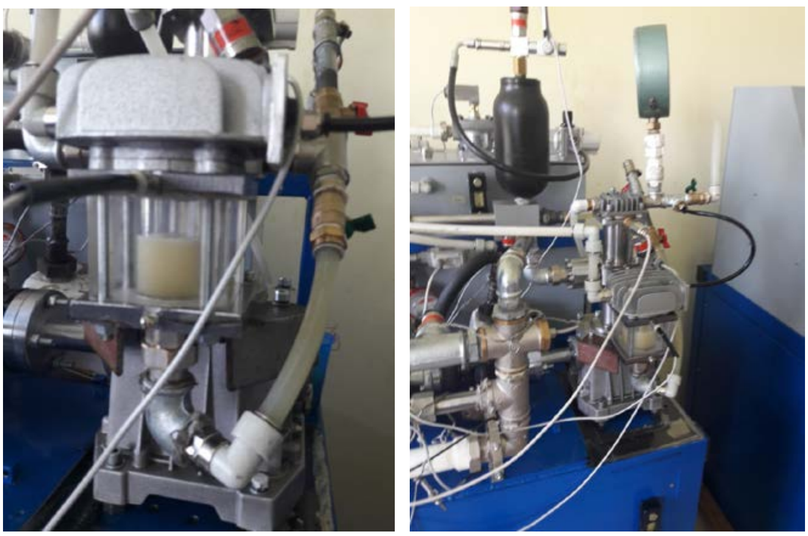

Figure 3. Exterior of PHEM.

The exterior of the developed experimental prototype of the two-stage PHEM is shown in Figures 3. The second-stage cylinder is made of plexiglass to study the liquid movement in the working cavity of the second stage, which allows to observe the movement of the liquid piston from bottom dead-centre to top dead-centre and in the opposite direction.

Table 1. Developed experimental prototype main characteristics

Description	**Values**
Diameter of the piston of the first stage, m	0.05
Piston stroke, m	0.05
Total working length of the cylinder, m	0.1
Piston length, m	0.049
Gap between the piston and the cylinder, μm	14
Length of the liquid line 12 l_3 from the sub-piston cavity to the branch in the gas cap, m	0.08
Length of the liquid line l_1 from the branch to the gas cap, m	0.55
Length of the liquid line l_2 from the branch into the gas cap to the working cavity of the second stage, m	0.377
Length of the gas inter-stage line 5, m	0.3
Diameter of the line l_1, m	0.013
Diameter of the line l_2, m	0.013
Diameter of the line l_3, m	0.002
Inner diameter of the gas cap, m	0.1
Height of the gas cap, m	0.24
Inner diameter of the working cavity of the second stage, m	0.04
Height of the working cavity of the second stage, m	0.061
Diameter of the line 5, m	0.006

3. Experimental description

This section describes the test bed and the main instrumentation. The test bed was designed and manufactured at the Section of Hydromechanics and Transport Machines of Omsk State Technical University within the framework of fulfillment of agreement 14.574.21.0068 “Development and design of new-type positive displacement energy-generating machines with increased heat exchange in the area of working bodies" and was used as a basic test bed for experimental research of the positive displacement two-stage PHEM. The test bed allowed to provide the following functions:

– possibility of smoothly changing the drive shaft speed of the machine with fixing the reciprocal action frequency of the piston;

– measurement and maintenance of constant thermodynamic parameters on suction and discharge lines of compressor and pump sections;

– measurement of instantaneous pressure values in the working cavities of compressor and pump sections, with the output of indicator diagrams in the digital and graphic forms;

– performance measurement of compressor and pump sections;

– measurement of leaks of the liquid and the gas;

– prompt action to the control parameters due to high ergonomic properties;

– measurement of temperature of gas and liquid in the suction and discharge lines of compressor and pump sections, as well as items of the cylinder-piston group.

The pneumatic-hydraulic circuit of the test bed is shown in Fig. 4. Air enters in the first stage of the compressor section CS1 of the positive displacement PHEM through the suction filter SF1 and the air flow rate meter at suction FIA1. Gas enters into the second stage of the compressor section CS2 of the positive displacement PHEM after the first stage through the discharge line, in which the pressure is measured by the gas gauge G3 and then through the metering and control instrumentation system to the gas consumer. The liquid from the pump P1 comes:

– through the control valve CV7 to the hydraulic accumulator AC1;

– through the liquid flow rate meter FIA4 and the control valve CV6 into the working cavity of the second stage of the positive displacement PHEM.

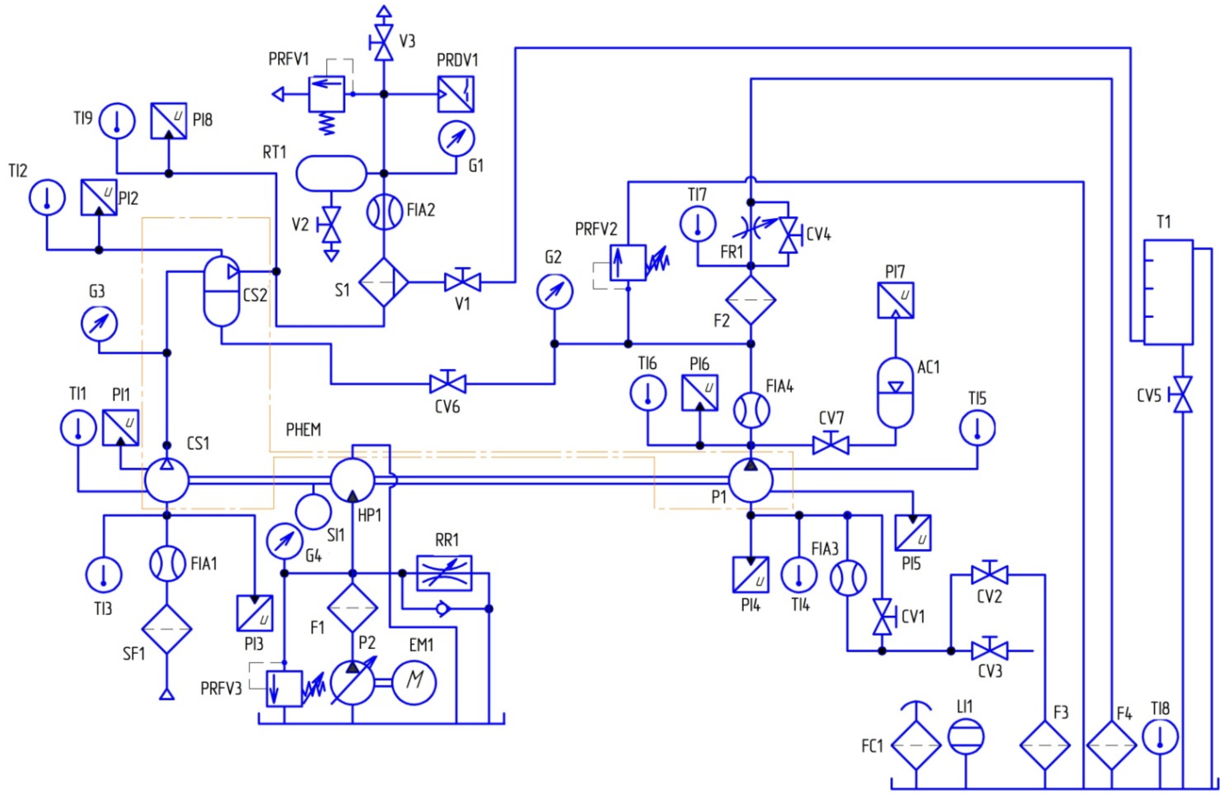

Figure 4. Pneumatic-hydraulic circuit of the test bed for researching the closed-crankcase positive displacement PHEM.

The test bed allows to test hybrid energy-generating machines in the range of the following pressures:

<u>Compressor section</u>

1. Suction pressure– 0.1 MPa.
2. Discharge pressure– 1.5 MPa.

<u>Pump section</u>

1. Suction pressure– 0.1 MPa.
2. Discharge pressure– 3.0 MPa.

The volumetric hydraulic drive is used in the test bed to smoothly change the drive shaft speed of the positive displacement PHEM, which includes the axial-piston pump with an adjustable capacity of model 313.3.56.804 and the discharge pressure of 6.3 MPa and the axial-piston hydraulic motor of model 310.3.56.01.03.V.U. Measurements of static pressures are carried out with type gauges MP3-UUHL1 with the maximum permissible basic error from the upper limit of ±1.0%, and instantaneous pressures with strain-gage pressure sensors of the type PSE530-M5-1 and MBS 3000 with non-linearity characteristics within ±1.0%.

As working substances were used: atmospheric air and petroleum base hydraulic oil MGE-46V with the properties shown in table 2:

A pneumatic accumulator (gas cap) with the Danfoss MBS 3000 pressure sensor is installed on a discharge line to reduce the irregularity in a pump section. A sensor of this type is also used to measure a suction pressure of the liquid. A measurement of liquid flow rates is carried out by TPR 20-8 flow meters, a measurement of suction and discharge temperatures by TW-N PT100 sensors, a liquid temperature in storages is measured by DTS-035-50M.V3 sensors. A leak measurement is carried out by the volumetric method estimation. Flowmeters of the models SMCPF2A751-F04-67N-M, "Vector-04" and SGV-15 "Betar" are used to measure the air flow at the suction and discharge of the compressor section. The model AD22100 STZ sensor is used to measure the stationary temperature of the valve plate and the top of a cylinder.

Table 2. Petroleum base hydraulic oil specification Rosneft MGE-46V

Indicator description	Normal value defined in the standard GOST
Kinematic viscosity, mm2/c:	
at 100°C, not less	6.0
at 50°C	-
at 40°C	41.4-50.6
at 0°C, not more	1000
viscosity index, not less	90
Temperature, °C:	
backfire in open cup, not less	190
solidification, not more	-32
acid value, mg KOH/g oil	0.7-1.5
Mass fraction:	
mechanical impurities, not more	default
water	default
metal corrosion test	withstands
density at 20°C, kg/m3, not more	890
Oxidation stability:	
oil residue, %, not more	0.05
changing of acid value, mg KOH/g oil, not more	0.15
Tribological characteristics at CWM:	
axial wear indicator 196 N, mm, not more	0.45

4. Experimental results

The conducted complex of experimental study made it possible to establish the following.

1. The developed experimental prototype turned out to be fully functional and provided gas compression in two stages.

2. The movement of the liquid piston in the range of changes in angular velocity from 250 rpm to 400 rpm was carried out in the second-stage cylinder similarly to the solid body (mechanical piston). The free surface of the liquid (interface) was like as the level surface parallel to the surface of the earth.

3. It was necessary to correctly configure the initial position of the phase interface in the second stage (initial position of the liquid piston) to increase the efficiency of the second stage. The liquid level in the second stage should approach the surface of the valve plate at the end of the discharge process. It was easy to control, because the cylinder was made transparent. In that case, if the liquid surface at the end of a discharge process was far from the valve plate, a significant reduction in the performance of the compressor section was observed due to significant clearance pocket, the rapid reduction in the volume factor and, in general, the conveyance factor. Fig. 5 shows indicator diagram of first and second stages in the presence of significant clearance pocket in the second stage.

4. The disadvantage of the operation of this system of the two-stage PHEM includes the difficulty of regulating liquid flows into the gas cap and into the working cavity of the second stage, especially at the starting modes of the compressor section.

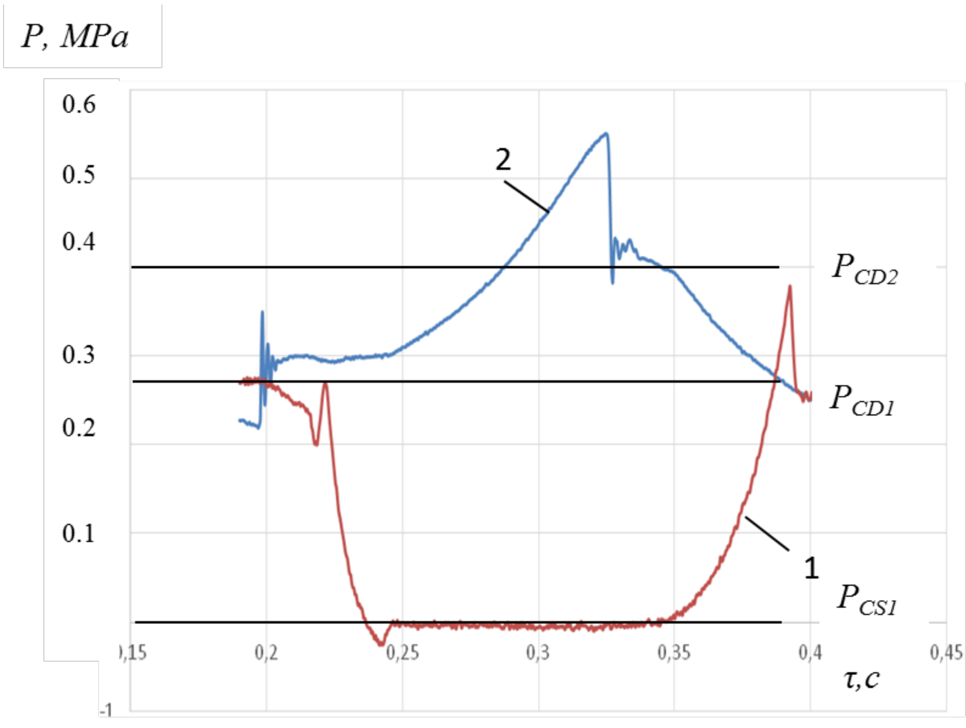

Figure 5. Indicator diagram of the first and second stages of the compressor section of the positive displacement two-stage PHEM:
1 – indicator diagram of the compressor section first stage;
2 – indicator diagram of the compressor section second stage;
P_{CS1} – suction nominal pressure of the first stage;
P_{CD1} - discharge nominal pressure of the first stage;
P_{CD2} - discharge nominal pressure of the second stage.

5. Discussion

The main advantages of the two-stage piston hybrid energy-generating machine for compressing gas to high pressures:

1. The use of a sub-piston cavity in the first stage, filled with liquid, allows for an intensive cooling of the items of the cylinder-piston group due to the flow of liquid from the sub-piston cavity through the piston seal into the working cavity of the first stage. It should be noted that the pressure in the sub-piston cavity 11 will always be higher or equal to the pressure in the working cavity 3, which requires a sufficiently good sealing of the first stage piston, and partial discharge of the liquid through the discharge valve 2 from the working cavity 3 to the inter-stage distribution pipelines and to suction of the second stage.

2. The presence of the liquid film above the first stage piston allows for an intensive cooling of the piston and the cylinder walls, as well as to eliminate clearance pocket. This is especially important because if gas is compressed in the two-stage compressor up to 10 MPa, then it is necessary to provide the compression ratio of about 10. In this case, it is necessary to bring the clearance pocket closer to 0 in order to obtain a high conveyance factor.

3. Installing the liquid piston in the second stage will allow for an intensive cooling of cylinder walls and the valve plate, which will bring the compression process closer to the isothermal process that is most advantageous from the thermodynamic point of view.

4. In addition, the presence of the liquid piston eliminates leaks in the piston seal; and if the initial position of the liquid piston (the initial volume of liquid in the swept volume 15) is correctly selected, it will allow to eliminate clearance pocket with no removal of liquid through the discharge valve 8 to the liquid consumer.

It should be noted that in this system there are certain disadvantages in addition to the advantages:

1. It is necessary to ensure the regulation of the resistance of hydraulic lines in the second stage into the gas cap so that the required amount of liquid enters in the second stage. This is especially difficult in compressor starting modes, when pressure changes in the working cavities.

2. As the working liquid, it is necessary to use the liquid with low viscosity, a high effective heat capacity and, most importantly, a low solubility of gas in it, so that the second stage liquid piston does not “foam”.

6. Conclusions

Based on the results of this work, the new principle diagram of the positive displacement two-stage piston hybrid energy-generating machine was considered. Also, based on an analysis of working processes and piston hybrid energy-generating machine units, the test bed of the two-stage PHEM has been developed, which allows the visualization of the movement of the liquid piston in the second stage of the machine using preliminary theoretical studies. The set of experimental studies on the previously developed and modernized test bed made it possible to prove the working capacity of the prototype, to measure the main thermodynamic and discharge parameters, and to identify the main features of an ongoing work process.

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