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Research and development issues on engineering prototype of the piston hybrid energy converting displacement machines


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Abstract

The paper deals with the process of engineering prototype development of the piston hybrid energy machine. The whole development process is divided into three main stages: constructional design, design engineering, process engineering and manufacturing. In the first stage the design of piston hybrid displacement machines is proposed. A mathematical model of pump and compressor section working processes of the hybrid machine is developed. At the design stage a pneumohydraulic scheme and design documentation are developed. At the final stage, measures to improve manufacturability and reduce the cost of piston hybrid machines are considered.

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1. Introduction

In the petrochemical and gas industry there is a wide application of piston displacement pumps and compressors that supply various gases: nitrogen, hydrogen, oxygen, etc. and fluids: gasoline, kerosene, oil, etc. under 20 MPa or higher pressure. The issue of development of the hybrid displacement energy machine, allowing to produce gas and fluid under pressure both simultaneously and interchangeably is of immediate interest.

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To date, a significant number of construction diagrams have been developed and research of the development of piston pump-compressors that combine the compressor and displacement pump functions in one unit has been conducted [1,2,3].

The study of pump and compressor combination in one unit has revealed its main advantages:
1. The increase of the compressor isothermal indicator of efficiency coefficient due to intensive cooling of the operating chamber walls by 3-5%.
2. The increase of piston compressor productivity and its efficiency increasing by compressed gas leaks eliminating in the piston seal by 5-7%.
3. Friction work reduction of in the piston seal due to fluid friction and increase of the mechanical coefficient efficiency by 7-8%.
4. Materials consumption reducing of the piston hybrid energy machines engineering prototype from 20 to 30%, due to drive components eliminating of the pump unit.

The whole process of piston hybrid energy machines engineering prototype development can be divided into three main stages: constructional design, design engineering, process engineering and manufacturing. All these stages are consistent described in the paper.

2. Piston hybrid energy machines constructional design

In the first stage of PHDM constructional design the advantages and disadvantages of cooling fluid injection in the displacement compressor working space have been analyzed. As a result of the effectiveness analysis of cooling fluid injection into the compressor operating chamber, its main shortfalls have been revealed and the idea of compressor working element and operating chamber surface area cooling due to their direct contact with the coolant has been proposed. This idea can be realized by using one of the compressor working cavities as the pumping cavity. The result of this decision, in addition to energy efficiency increase of the compressor section due to its cooling and friction reducing in the working elements zone, is an additional machine function which is pump function. Thus, there is an engineering solution with pump and compressor functions and capability of performing these two functions both together and interchangeably. Subsequent analysis of the areas of gas and fluid simultaneous use under pressure has shown that a large number of both domestic and foreign industry facilities need the combined use of fluid and gas under pressure, giving evidence of the engineering solution significance.

As a result of the patent research in the following countries: Russia, Ukraine, China, USA, Spain, Japan, Germany, Mexico, more than 350 patents and literary sources for 10 years (from 2004 to 2014) were examined. The result is that the patent research has revealed structural solution for blocked and non-blocked machines for gas and fluid compressing simultaneously and interchangeably. Based on the patent search a long-range PHDM design has been offered shown in Fig. 1.
The proposed design of hybrid piston energy machine allows to cool a compressor operating chamber surface area intensively, almost avoid leakage and decrease the friction work and reduce cylinder-piston group component wear. The design has highly compactness and it allows to obtain gas and fluid under pressure, while having separate lubrication movement mechanism.

To study the compressor section operating process we have developed a mathematical model based on the use of the basic conservation laws: energy, mass and movement, as well as the equation of state. Using a system of simplifying assumptions [1], a system of differential equations, which allows to calculate the thermodynamic parameters values of the gas in the variable and constant volume cavities, can be written as follows:

\[
\frac{dU}{dt} = dQ - dL + \sum_{i=1}^{N_1} i_n dM_{ni} - \sum_{i=1}^{N_2} i_o dM_{oi}
\]

(1)

\[
dM = \sum_{i=1}^{n_1} dM_{ni} + \sum_{i=1}^{n_2} dM_{oi}
\]

(2)

\[
\frac{dp}{p} + \frac{dV}{V} = \frac{dM}{M} + \frac{dT}{T}
\]

(3)

\[
m_{np} \frac{d^2 h}{dt^2} = \sum_{i=1}^{N_1} F_i
\]

(4)
where \( P, V, M, T \) are pressure, volume, mass and temperature of the compressed gas; \( U \) is a total internal energy; \( i \) is a specific enthalpy; \( dL \) is elementary contour work; \( m_{пр} \) is self-operated shut-off valve reduced mass; \( \sum_{i=1}^{N_3} F_i \) is the sum of the forces acting on the self-operated shut-off valve, including the gas pressure force, the spring elastic force and friction force and the mass force; \( N_1, N_2 \) is the number of compressed gas inlets and outlets into the working cavity; \( h \) is current self-operated shut-off valve height; \( \tau \) is time.

Computational scheme for the mathematical model of PHDM operating processes is presented in Fig.2. Elementary \( dq \) external heat transfer \( dQ \) and mass flows are based on the Newton-Richman hypothesis and the Saint-Venant-Vantsev flow-rate equations.

Mathematical model of the pump section processes is based on the basic fundamental laws: conservation of energy, volume, mass, motion and also the Hooke law. The system of differential equations for determining the fluid pressure, mass and volume in the pump working chamber of can be written in the following form:

\[
dz + \frac{dp_w}{\rho g} + \omega_w d\omega_w + dh_w = 0 \tag{5}
\]

\[
dV_w = dV_{\text{sumw}} - \sum_{i=1}^{N_1} dV_{0iw} + \sum_{i=1}^{N_1} dV_{niw} \tag{6}
\]

\[
dM_w = \sum_{i=1}^{N_1} dM_{niw} - \sum_{i=1}^{N_2} dM_{0iw} \tag{7}
\]

\[
dp_w = -E \frac{dV_w}{V_w} \tag{8}
\]

\[
m_{прw} \frac{d^2 h_w}{d\tau^2} = \sum_{i=1}^{N_1} F_{iw} \tag{9}
\]

where \( p_w, \omega_w \) is the fluid pressure and velocity; \( z \) is the section gravity center; \( h_w \) is pressure loss; \( M_w, V_w \) are the fluid mass and volume in the working chamber; \( E \) is the apparent elasticity module including elasticity modulus of fluid and cylinder walls material; \( N_2, N_3 \) is the number of compressed gas inlets and outlets into the pump working cavity; \( dV_{\text{sumw}} \) is a basic change in the working chamber volume due to the kinematics of the crank-crosshead beam mechanism; \( m_{прw} \) is the reduced mass of the pump self-operated shut-off valve; \( h_{шк} \) is the current height of the pump self-operated shut-off valve; \( \sum_{i=1}^{N_1} F_{iw} \) sum of the forces acting on the self-operated shut-off valve.
Darcy-Weisbach and Borda and others equations have been used to determine the pressure loss.

The algorithm of operating process mathematical modeling is based on the use of an iterative method, calculation data from the previous cycle being taken as the initial data of the next full cycle. The process lasts until the end results match the previous calculation results with required accuracy. For obtaining rational values of the basic construction parameters the mathematical model was implemented in the Fortran algorithmic language in «Co-Arrays Fortran» programming package. The results of calculations for the operating parameters are: rotational speed is 500 r/min, the compressor suction pressure is 1 bar and compressor discharge pressure is 8 bar, the suction pump pressure is 1 bar; pump discharge pressure is 30 bars. The basic construction sizes are: piston stroke is 50 mm; piston diameter is 90 mm; the length of the piston is 146 mm; crosshead diameter is 52 mm; the crosshead length is 146, 5 mm; the piston rod diameter is 22 mm; the clearance in the piston seal is 100 mkm; relative clearance pocket of the compressor cavity is 3.6%.

3. Piston hybrid energy machines design engineering

At the stage of PHDM design engineering, a pneumohydraulic scheme and constructional documentation have been developed.

The pneumohydraulic scheme is shown in Fig. 3. It provides a hydraulic lines purge from pressure fluid with its simultaneous draining into a source flow, as well as organizing "Compressor", "Pump", "Pump-compressor" PHDM modes. Modes switching is done by a slide-type valve.

Pneumohydraulic PHDM scheme is composed of:
- Cleanup system of the sucked and discharged of air from dust particles and liquid drops;
- Oscillation control system of compressed air supplied to the customer;
- Automatically control system of PHDM operations which includes: monitoring of the compressed gas discharge pressure, a safety valve is triggering on pressure raising to a maximum value which is 1.3 times higher than the nominal.
Fig. 3. PHDM pneumohydraulic scheme: A1 is PHDM, KM1 is a piston compressor, H1 is a piston pump, AT1, AT2 – are heat exchangers, ВД1 is a moisture collector, ВН1-ВН5 is a valve, K1, K2 is a pneumatic valve, КП1 is a pneumatic valve safety relief, КП2 is a hydraulic valve safety relief, МН1, МН2 is a pressure gauge, P1 is a hydraulic control valve, РД1 is a gauge pressure switch, РС1 is a receiver, Ф1-Ф3 is a filter, ППК1 is a passageway.

The obtained dimensions were used for creating a 3D model (see. Fig. 4) of the machine in COSMOSWorks, which tested the structural assembly and operational integrity, as well as the durability of the main parts and construction units.

Fig. 4. 3D model of the PHDM discharge unit: 1. Cylinder. 2. Piston. 3. Crosshead. 4. Piston rod. 5. Crankshaft. 6. Bearing.
The finite-element mesh with a side elements average size of 3 mm has been used for the calculations. The total number of elements is 241,604, the number of contraction units is 369410. In the calculation a controlling case is considered: the piston is loaded with the maximum load in the middle of a full stroke, with its maximum speed.

For strength analysis the following assumptions were made: the axial load on the crankshaft is negligible; strength of welded joints is considered equal to welded parts strength analysis, provided the weld type and size, welding technology and control. Calculations of bolted joints and bearings were carried out separately; loads applied to the mechanism details are equal to the maximum pressure force in the pump and compressor sections; there is pin-edge fixing in bearings.

Some results of the calculations are presented in Fig. 5. According to the results we can conclude the necessary safety margin of a construction.

![Fig.5. Calculation results of 3D model PHDM discharge unit.](image)

4. Piston hybrid energy machines process engineering and manufacturing

New products manufacturing involves a detailed study of machine parts, construction units and assemblies manufacturing processes. In the initial stage of the PHDM manufacturing preparation process the fabricability test was carried out. Some shortcomings of the construction was found, which led to its significant rise in price. However, the undertaken measures for improving the manufacturability allowed to reduce the PHDM manufacturing cost at about 35%.

The main measures include the following: replacement of expensive materials for cheaper ones at the same workability and wear and corrosion resistance, increasing of parts dimensional tolerances without changing the product functionality, increasing of the surface roughness parameters.

In order to improve PHDM manufacturability the piston rod sizes, the threaded elements (nozzles) and the piston rings were adjusted. The adjustment allowed to provide specially designed parts replacement for the parts produced in large-scale production of automotive and pipeline fittings industries.

The principal adjustments were for PHDM cylinder. After the calculations using mathematical models the required dimensions of the suction and discharge passage sections have been determined but the parameters would lead to an increase in the overall unit dimensions. It was suggested to change the number of suction and discharge lines from one to four. This enabled the calculated value of the flow cross section lines and apply standard fitting
with \( \frac{3}{4} \) inch threads. Cylinder bore has met the standardization and unification requirements, enabling to use of standard piston rings, as well as to improve the product manufacturability.

Essential measures on the piston PHDM manufacturability improvement were also carried out (Fig. 6). Changes in the piston construction were in the place by crosshead fixation to the cylinder. It has been proposed to use a special screw for piston fastening to the crosshead. It made possible to increase the diameter of the screw head and as a result to provide a margin of safety in tension.

Fig.6. PHDM piston.

The crankshaft construction was made combined. It allowed to avoid the use of special equipment in its manufacture.

5. Conclusions

1. On the basis of the literature and patent sources analysis of variable areas of compressed gas and fluid under pressure simultaneous and interchangeable use, as well as the analysis of the advantages and disadvantages of the coolant injection into the displacement compressor working cavity, the PHDM piston construction of a new type has been developed for the of gases and fluids production under pressure.

2. At the stage of constructional design a mathematical model for pump and compressor sections operating processes has been developed allowing to calculate the rational values of PHDM basic geometric parameters and ratios.

3. At the stage of constructional design a PHDM pneumohydraulic scheme has been developed, as well as strength calculation has been conducted, which showed the necessary safety margin the machine main parts and components in operating at gas pressure of 0.8 MPa and liquid pressure of 3 MPa.

4. Manufacturability improving and cost reducing measures have been considered. Their implementation has reduced the engineering prototype cost by 35%.
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