Investigation of the energy-saving hydraulic drive of a multifunctional automobile with a subsystem of accumulation of compressed air energy

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Abstract. A mathematical model of the operation of the pneumatic subsystem of the compressed air energy storage device and the computer program developed on its basis are presented, which made it possible to investigate the influence of the geometric and thermophysical parameters of the pneumatic system elements on the efficiency of energy storage and heat losses.

1. Introduction

One of the promising and realizable ways to increase the efficiency of a multifunctional automobile, for example, for the removal of timber or the care for forest shelterbelts, is to equip it with recuperative mechanisms that ensure the repeated use in the work process of energy that is not efficiently dissipated into the environment, and also contribute to improving reliability and simplifying its construction. «Figure 1» presents the scheme of the device developed by the authors for accumulating the energy of compressed air in the hydraulic drive of a multifunctional automobile.

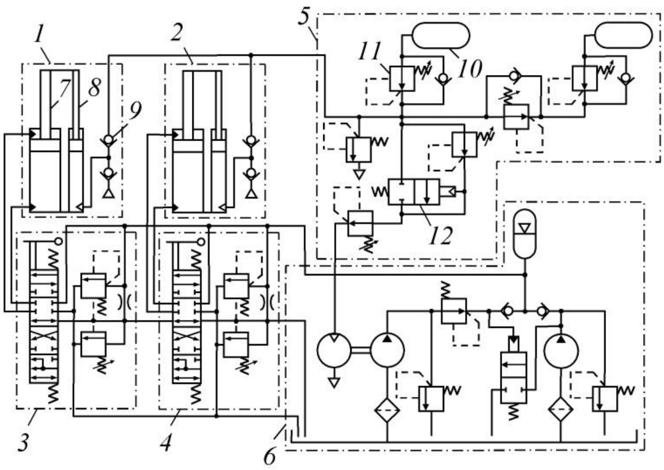

Figure 1. Scheme of the device for accumulating compressed air: *1*, *2* – energy recovery mechanisms; *3*, *4* – hydraulic distributors, *5* – pneumatic accumulator unit; *6* – hydraulic pump unit; *7* – the

hydraulic cylinder, *8* – pneumatic cylinder; *9* – reverse pneumatic valve; *10* – receiver; *11* – reduction pneumatic valves; *12* – pneumatic two-position distributor

One of the serious problems of the practical implementation of the proposed scheme is the importance of increasing the efficiency of accumulation of compressed air energy in the receiver, by reducing the thermal losses of energy stored in it. The main reason for this is the occurrence of free convection, which increases the heat transfer to the walls of the receiver with a significant increase in air temperature during its rapid compression, long storage, and with a sharp decrease in air temperature during its expansion. A negative consequence of this heat and mass transfer is the appearance of moisture, the freezing of the elements of the pneumo-mahogany and the pneumatic engine with the expansion of compressed air [1-6].

2. Materials and methods

To solve this problem, a mathematical model was developed for the operation of the pneumatic subsystem of a multifunctional automobile that encompasses the kinematics of an air cylinder, heat transfer processes in the main pneumatic elements and the processes of transferring compressed air between them. To achieve sufficient universality, the model is based on numerical methods.

From the elements of the pneumatic subsystem, three types of elements that have a significant influence on the process of energy storage and heat losses are chosen for modeling: pneumocylinders, coupled with hydraulic cylinders of the manipulator; pipelines between pneumatic cylinders and receivers; receivers. For each of the listed elements, a separate model has been developed that reproduces both the transfer and change of the state of the gaseous medium and the heat and mass exchange processes. Consider the compilation of the model by the example of the most complex element – pneumatic cylinder.

Modeling of heat propagation is complicated by the need to transfer to the model the elements of the pneumatic system with high detail and spatial resolution, as well as the ability to specify different laws of movement of the rod of the pneumatic cylinder. In this case, it is important to take into account the peculiarities of both single movement of the piston rod during the operation of the multifunction machine, as well as multiple, including periodic motion. Therefore, a simplified analytical model of heat transfer is used, but a grid finite-difference numerical method. The model is based on the basic equations of classical thermodynamics. The complexity of the problem described above is overcome by using the discretization of space with a cubic grid and discretization of time. In the three-dimensional case, the propagation of heat is described by «equation (1)» of thermal conductivity:

$$\frac{\partial}{\partial t}T(\vec{r},t)=\left(\nabla,\ \chi(\vec{r},t)\nabla T(\vec{r},t)\right)+Q(\vec{r},t), \tag{1}$$

Where $T(\vec{r},t)$ – the distribution of temperature in space and its variation over time; $\vec{r}$ – radius of the point of space; t – time; $\nabla=\frac{\partial}{\partial x}\vec{i}+\frac{\partial}{\partial y}\vec{j}+\frac{\partial}{\partial z}\vec{k}$ – differential operator; x, y, z – cartesian coordinates of the space point under study; $\vec{i},\vec{j},\vec{k}$ – unit vectors in the cartesian space; (,) – scalar product; $\chi(\vec{r},t)$ – coefficient of thermal conductivity of matter; $Q(\vec{r},t)$ – the field of heating and cooling sources that changes over time.

To transmit in the model the shape and structure of the pneumatic system elements with sufficient detail, the space in which the simulation is performed is discretized by a rectangular grid with a pitch of h = 5 mm. The grid dimensions in the three spatial directions X, Y, Z are 150 × 60 × 60 knots; the total number of nodes is 540000, which makes the model sensitive to the performance of computer technology. Each grid node for solving the heat conduction equation has six adjacent nodes from which heat can be received, or which transfers heat (Figure 2).

In the finite-difference formulation of the problem «equation (1)» can be rewritten as follows:

$$\frac{\Delta T_{i,j,k}}{\Delta t} = \chi_{i,j,k}\left(\frac{\Delta T_{i,j,k}}{\Delta x} + \frac{\Delta T_{i,j,k}}{\Delta y} + \frac{\Delta T_{i,j,k}}{\Delta z}\right) + Q_{i,j,k}, \tag{2}$$

where (i, j, k) – host indexes; $T_{i,j,k}$ – knot temperature; Δt – step of time sampling (0.1 s); $\Delta x = \Delta y = \Delta z = h$ – step of discretization of space; χ – coefficient of thermal diffusivity; $Q_{i,j,k}$ – supply of heat from the external environment to this cell.

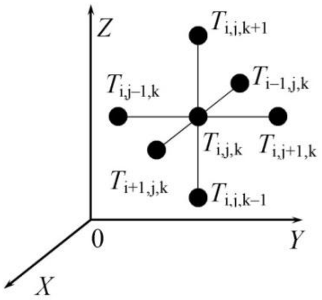

Figure 2. Cross-like scheme of accounting for neighboring nodes in the grid solution of the heat equation.

Describing in detail the finite differences in «equation (2)» and transforming, we obtain the following final «equation 3» for modeling the propagation of heat:

$$\frac{T^{\tau+1}_{i,j,k} - T^{\tau}_{i,j,k}}{\Delta t} = \frac{\chi_{i,j,k}}{h}\left(T^{\tau}_{i+1,j,k} + T^{\tau}_{i-1,j,k} + T^{\tau}_{i,j+1,k} + T^{\tau}_{i,j-1,k} + T^{\tau}_{i,j,k+1} + T^{\tau}_{i,j,k-1} - 6 \cdot T^{\tau}_{i,j,k}\right) + Q_{i,j,k}. \tag{3}$$

The last «equation 3» allows us to calculate the temperature $T^{\tau+1}{}_{i,j,k}$ of each cell (i, j, k) for the next step of time integration $\tau + 1$, based on the current temperature $T^{\tau+1}{}_{i,j,k}$ of the current integration step τ.

The problem of heat propagation is solved for media of two types: the metal from which the element of the pneumatic system and the heat-insulating material is made, which is surrounded by the element of the pneumatic system. The working gas of the pneumatic system is modeled separately: in the homogeneous gas approximation it is considered that the convective processes in the gas in each pneumatic element proceed much faster than the processes of heat propagation. The heat exchange between the pneumatic system element and the surrounding air is reproduced in the model by setting the boundary conditions on the external surface of the pneumatic system elements. Thus, the grid thermal problem is not solved for the surrounding gaseous medium and the working gas medium, for which the change in the state as a whole and the mass transfer between the elements of the pneumatic system are modeled.

A particular difficulty is the consideration in the thermal problem of the movement of the rod and the piston of the air cylinder. On the basis of the law of motion of the piston $x_c(t)$ at each step of integration τ, the real number x is bound to the grid by rounding to an integer, and shifting left or right in the grid model of the set of nodes belonging to the movable part of the air cylinder (piston with rod). In this case, the displacement of nodes means the assignment of temperatures and types of nodes with a shift to the left or to the right.

Parallel to the solution of the thermal problem, a numerical simulation of the change in the state of the working gas and its transfer between the elements of the pneumatic system are carried out. Simulation is performed by numerical methods on the basis of the Euler method, with the same integration step Δt as for the thermal problem. Consider the example of a pneumatic cylinder algorithm for modeling the

change in the state of the working gas and the displacement between the elements of the pneumatic system (in the finite-difference formulation of the problem).
The movement of the piston of the pneumatic cylinder is a source of disturbance in the system under consideration. In the model, trapezoidal and sinusoidal laws of piston motion are verified. The latter is given by «equation 4»:

$$x_c(t) = x_{c0} + A_x \sin(\frac{2\pi}{T_n} t), \tag{4}$$

Where x_c – distance from piston to the end of the working cavity of the air cylinder; x_{c0} – piston position at the initial time; A_x – piston displacement amplitude; T_p – period of harmonic displacement of the piston.
Based on the current position of the piston $x_ц^\tau$, the current volume of the working cavity of the air cylinder V_c^τ is calculated on the basis of the «equation 5» at this integration step τ:

$$V_c^\tau = x_c^\tau \pi \frac{D_c}{4}, \tag{5}$$

Where D_c – internal diameter of air cylinder.
Then, according to «equation 6», a new working gas pressure is calculated using the ideal gas approximation and the adiabatic process equation. The adiabatic approximation is accepted, since for a short time interval Δt the change in the gas state is more pronounced than the heat removal.

$$P_c^\tau = P_c^{\tau-1} \left(\frac{V_c^{\tau-1}}{V_c^\tau} \right)^{\frac{i+2}{i}}, \tag{6}$$

Where P_c^τ и $P_c^{\tau-1}$ – working gas pressure in the air cylinder at the current and previous integration steps; V_c^τ и $V_c^{\tau-1}$ – the volume of the working cavity of the air cylinder at the current and previous steps of integration; i – number of degrees of freedom of gas molecules (for air with a high degree of accuracy $i = 5$)
Then the gas temperature T_c^τ is calculated from «equation 7» of the ideal gas state:

$$T_c^\tau = \frac{P_c^\tau V_c^\tau}{\nu_c^\tau R}, \tag{7}$$

Where ν_c^τ – the amount of substance in the working cavity of the pneumatic cylinder, which varies as the air enters and leaves the working cavity; R – universal gas constant.
Further, depending on the pressure P_c^τ, the amount of the gas flowing from the atmosphere (at P_c^τ less than atmospheric pressure P_a) or transferred to the receiver (at P_c^τ more than a certain pressure P_p^τ passing gas into the recuperative pneumatic system) is calculated:

$$Q_c^\tau = \begin{cases} k_a \sqrt{P_a - P_c^\tau}, \ P_c^\tau < P_a; \\ 0, \ P_a \le P_c^\tau \le P_p^\tau; \\ -k_p \sqrt{P_c^\tau - P_p^\tau}, \ P_c^\tau > P_p^\tau, \end{cases} \tag{8}$$

Where k_a – coefficient of throttling in the inlet of atmospheric air; k_p – reduced throttling factor for the air path from the pneumatic cylinder to the receiver (in the accumulation mode), or to the pneumatic motor (in use mode). Using the value of the flow Q_c^τ, the change in the current step τ of the amount of

substance v_c in the working cavity is calculated.
In the same way, heat and mass transfer processes are simulated in other main elements of the pneumatic system: the receiver and the conditional pipeline connecting the air cylinder and the receiver.

3. Results
For the convenience of the simulation, a computer program "Program for modeling the energy-saving hydraulic drive of a multifunctional car with compressed air storage subsystem" in Object Pascal language in the Borland Delphi 7 integrated programming environment was developed. The program allows to set the geometric and thermal parameters of the pneumatic system elements and to investigate their effect on the energy storage efficiency and magnitude of heat losses. In the process of work, the program regularly displays on the screen two projections of the investigated element of the pneumatic system, temperature distribution charts in sections, temperature profiles in specified directions. The program is designed to use a computer with a processor not lower than the Pentium 2.3 GHz, and the amount of RAM is not less than 512 MB. The source code for the program is 12 KB.
Computer experiments with the developed model consisted in repeated movement of the piston of the pneumatic cylinder by a sinusoidal law simulating the work of a combined hydraulic and pneumatic cylinder in the manipulator in the technological cycle. In the course of the experiment, the spatial distribution of the temperature changed and gradually came to the steady-state cycle «Figure 3».

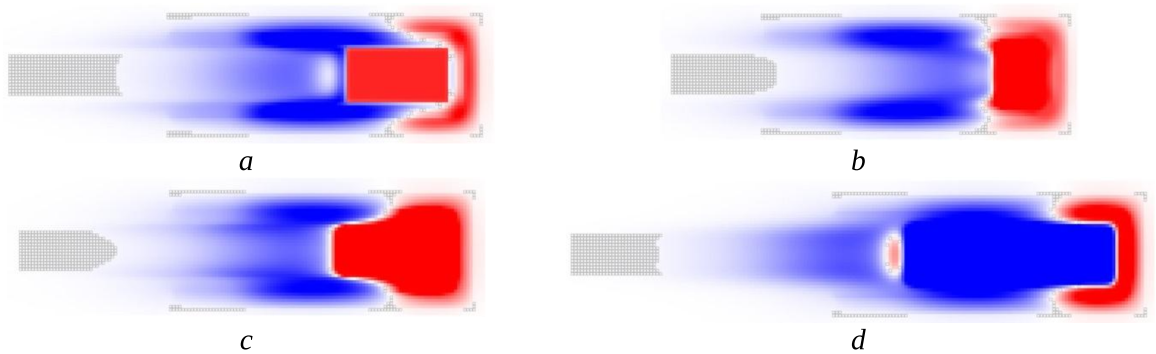

Figure 3. Cartograms of the spatial distribution of temperature in the pneumatic cylinder in different phases *I* .... *IV* of the steady-state duty cycle: *a* – phase *I* (the piston moves to the right); *b* – phase *II* (maximum compression); *c* – phase *III* (the piston moves to the left); *d* – phase *IV* (maximum discharge).

When the piston moves to the right (Figure 3, *a*) gas in the working cavity is compressed (Figure 3, *b*), which leads to its heating and spreading of high temperature into the walls of the pneumatic cylinder and a layer of thermal insulation around the working cavity. The movement of the piston to the left «Figure 3, *c*» leads to the expansion of the working gas, because of which the gas cools down below the ambient temperature (Figure 3, *d*). The reduction in temperature covers the walls of the pneumatic cylinder, piston and rod.
Despite the fact that the cooling area covers a larger volume, the maximum temperature decrease does not exceed 30 K (Figure 4). At the same time, in the region of heating, smaller in volume, the heating of the wall of the pneumatic cylinder can reach 75 K, cyclically varying from 25 to 75 K.

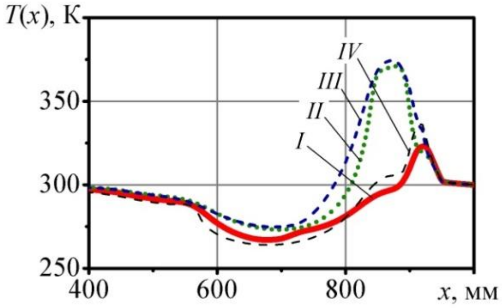

Figure 4. Temperature profiles along the metal wall of the pneumatic cylinder along the length x in different phases I ... IV of the steady-state duty cycle.

Because of the loss of heat, the gas in the working cavity reduces its internal energy, which does not allow the accumulation of a certain part of the mechanical energy of the piston motion by the pneumatic system. To evaluate the energy losses of the compressed air recuperation system in a pneumatic cylinder, a series of computer experiments was performed in which the thickness of the heat-insulating layer b around the air cylinder from 0 to 40 mm in increments of 5 mm was changed. As a material for a heat insulator, a group of inorganic materials with a thermal conductivity of 0.040 W / (m · K) is considered. As a measure of energy loss, the difference $\Delta E_p = E_м - E_g$ is accepted between the mechanical work $E_м$ on the displacement of the piston in a pneumatic cylinder during the inflation of air and the energy of compressed air E_g, available for use in the future. For convenience of perception, the relative energy losses $\Delta E_p/E_м$ are analyzed, that is, the share of energy losses in the total work on the accumulation of compressed air (Figure 5).

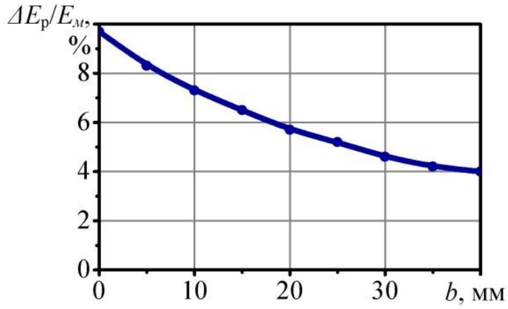

Figure 5. Influence of the thickness b of the thermal insulation layer of the air cylinder on the thermal energy loss $\Delta E_p/E_м$ in it with the accumulation of compressed air

Improvement of thermal insulation leads to a significant reduction in energy losses «Figure 5». The greatest decrease in losses – from 9.7 to 5 % – occurs at a thickness of the heat-insulating layer 20 ... 30 mm. Further increase in the thickness b is not advisable, since it almost does not lead to a reduction in heat losses (about 1 % with an increase in b from 25 to 40 mm), but it requires a considerable increase in the dimensions of the air cylinder.

4. Conclusion

Thus, a mathematical model is developed and implemented in the form of a computer program that allows to investigate the influence of the geometric and thermophysical parameters of the elements of the pneumatic system, as well as the operating conditions of the multifunction machine, on the efficiency of energy storage and heat losses.

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