Modeling of gas exchange processes of a four-stroke piston engine with ignition from an external source

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Abstract. Features of mathematical model construction of gas exchange processes of the four-stroke piston engine and, in particular, statement of initial and boundary conditions are described. The vibrational process of the air column in the intake and exhaust manifolds is considered. The parameters of working processes neglected in the calculation model are specified. The most significant factors for the mass filling of cylinders are determined. The results of calculating the velocity of the working fluid in the exhaust body in the area between the exhaust valve and the first branching are presented.

1. Introduction

The process of removing the used working fluid from the cylinder and filling it with a fresh charge is a complex non-equilibrium gas-dynamic process accompanied by heat and mass transfer. Changing the parameters of the state of the working fluid in the cylinder is determined by a number of physical processes, namely [1, 2, 3]:
- consumption of the working fluid through the outlet and inlet;
- the mixture coming into the cylinder of the engine of the fresh charge with the hot residual gases;
- the change in the volume of the gas mixture as a consequence of changing the piston position;
- a heat exchange of gas mixture with the walls of the cylinder, the bottom of the piston, the Poppet valves of valve timing and cylinder cover;
- fluctuations in the state of the working fluid due to gas-dynamic phenomena.

Full and accurate account of all these factors requires construction of a fairly complex mathematical model of gas exchange processes. Currently, there are two main approaches to the analysis of processes of gas exchange in reciprocating engines: an approach based on the principle of isotropy of the working fluid, and the approach where the equations of gas dynamics are used to analyze the motion of the gas in the intake and exhaust bodies.

2. Modeling review

On the basis of the first approach, a number of calculation methods have been created allowing to take into account and investigate the influence of such factors as the order of operation, the number of cylinders united by one collector, the design parameters of the gas distribution bodies (the number and diameters of inlet and outlet holes, the gas distribution phase, the volume of collectors, and so on) and others. However, the principle of isotropy of the working fluid, which is the basis of these methods, excludes the possibility of estimating the distribution of gas parameters along the length of the gas-air
path and, as a consequence, the wave adjustment of the intake bodies by calculation. These methods are used in estimating characteristics of the gas exchange system, especially for low-speed engines.

Methods based on solutions of well-known basic equations of gas dynamics have significantly greater capabilities. The parameters of the gas flow to be calculated are determined by three conservation laws: the laws of conservation of mass, momentum and energy [4, 5, 6]:

\[
-\frac{\partial}{\partial t} \int \rho \cdot dV = \oint \rho \left( \hat{W} \cdot d\vec{F} \right)
\]

\[
-\frac{\partial}{\partial t} \int \rho \cdot \hat{W} \cdot dV = \oint \rho \cdot \hat{W} \left( \hat{W} \cdot d\vec{F} \right) + \oint p \cdot d\vec{F}
\]

\[
-\frac{\partial}{\partial t} \int \rho \cdot E \cdot dV = \oint \rho \cdot E \left( \hat{W} \cdot d\vec{F} \right) + \oint p \cdot \left( \hat{W} \cdot d\vec{F} \right)
\]

where \( \rho \) – local density, kg/m\(^3\);
\( V \) – cylinder volume, m\(^3\);
\( W \) – local flow rate, m/s;
\( F \) – surface area of the flow, m\(^2\);
\( p \) – total pressure, Pa;
\( E \) – total energy, J.

Within the framework of a specific physical problem of modeling the gas exchange processes in a four-stroke piston engine, the most rational mixed approach for this type of engines was used: the problem of the cylinder, which consists in determining parameters of the working fluid state at each time during the gas exchange process, is solved on the basis of the principle of isotropy; and the search for a solution to the problem of the intake and exhaust bodies, which is to determine the distribution of the parameters of the working fluid state along the length of the intake and exhaust bodies at each time during the gas exchange process, is carried out by the difference method on the basis of gas dynamics equations.

The solution of the cylinder problem can be found by numerically solving a first-order nonlinear differential equation composed for an open thermodynamic system: \( dp = f (dt) \). However, the search for such a particular solution of the above-mentioned equation, which would describe the change in the parameters of the state of the working fluid in a particular engine, requires specifying the initial and boundary conditions [7].

The initial conditions include the pressure, temperature and weight of the working fluid enclosed in the engine cylinder at the time of the outlet opening. These initial conditions are determined by the characteristics of the crank mechanism (CR) - the initial volume of the working fluid enclosed in the cylinder, the characteristics of the gas distribution mechanism (GDM) - the outlet opening, and the characteristics of the actual cycle - the initial mass, temperature and composition of the working fluid. All these initial conditions can be determined for a particular engine based on its actual cycle and its design characteristics.

The boundary conditions include the value of the effective passage area of the inlet and outlet, pressure, density and temperature of the working fluid in the intake and exhaust bodies at the inlet and outlet opening. Thus, in order to solve the problem of the cylinder, it is necessary to solve the problem of inlet and outlet bodies.

In the course of solving the problem of the intake and exhaust bodies, such insignificant factors as the forces of internal friction, thermal conductivity, gas and etc., including even weaker processes, were neglected, assuming quasi-one-dimensional nature of the flow of the working fluid in the intake and exhaust bodies. Within the framework of the assumptions made, the system of equations (1) can be transformed [8] to the following form after calculating the corresponding integrals:
\[
\frac{\partial}{\partial \alpha} \left( \frac{2}{k-1} \cdot a + W \right) + \left( W + a \right) \frac{\partial}{\partial \alpha} \left( \frac{2}{k-1} \cdot a + W \right) = 0
\]

\[
\frac{\partial}{\partial \alpha} \left( \frac{2}{k-1} \cdot a - W \right) + \left( W - a \right) \frac{\partial}{\partial \alpha} \left( \frac{2}{k-1} \cdot a - W \right) = 0
\]

where \( a \) – local speed of sound, m / s;
\( W \) – local flow rate, m / s;
\( k \) – adiabatic index.

The system of equations (2) has an infinite number of partial solutions. The search for such a particular solution of the above-mentioned system of equations, which would describe the change in the parameters of the state of the working fluid in the inlet and outlet of a particular engine, requires specifying the initial and boundary conditions.

The initial conditions include distribution of pressure, temperature and density of the working fluid enclosed in the inlet and outlet of the engine at the beginning of the outlet opening.

The specified initial conditions are determined by the joint action of CR (creating forced oscillations of the column of working fluid), GDM (forming the profile of the propagating finite-amplitude waves) and the bodies of the intake and exhaust (forming self-oscillations of the column of working fluid). The initial conditions of the inlet and outlet bodies problem were determined by iteration, where distribution of the working fluid parameters along the length of the inlet and outlet bodies was assumed to be uniform in the zero approximation.

The boundary conditions include the condition of non-flow at the closed boundary of the pipeline and the parameters of the working fluid at the open boundaries of the pipeline.

3. Results

The solution of the system of equations (2) was carried out by the grid-characteristic method using an implicit difference scheme. The influence of processes in the adjacent branches of the inlet and outlet [9, 10], serving other cylinders of the multi-cylinder engine, was carried out by analogy with the injector.

The described mathematical model was implemented in a standard subset of the C++ programming language as a package of applications. An example of the resulting numerical calculations is shown in Figure 1.

**Fig 1.** Velocity of the fluid in the exhaust area between the exhaust valve and the first branch

As already mentioned, the boundary conditions include not only the parameters of the state of the working fluid in the inlet and outlet bodies at the physical boundaries, but also the law of change in
time of the effective passage area of the inlet and outlet openings.

Thus, the above-mentioned boundary condition participates in formation of the functional dependence \( dp = f(dt) \) and directly, along with the characteristics of the CR and intake and exhaust bodies, participates in formation of dependencies describing a change in the parameters of the working fluid state in the engine cylinder.

Traditionally, the formulation of boundary conditions is to determine parameter values of the working fluid state, and the effective passage area of the holes is considered as a predetermined value, determined in the course of solving the problem of GDM taken isolated from solving problems of the cylinder and the inlet and outlet.

The peculiarity of the boundary conditions in this model is that the effective passage area of the inlet and outlet holes is considered as a freely variable parameter, which is part of the specified boundary conditions and is selected in such a way as to ensure the lowest value of the pump strokes at the highest cyclic mass filling of the cylinder with a new charge.

4. Conclusion

The described approach to the boundary conditions allows to simulate the effect of targeted modernization of GDM on the gas exchange processes in the piston engine under consideration and to solve the problem of selecting the effective passage area of the inlet and outlet holes in the course of computational rather than full-scale experiment.

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