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The Influence of Cross-profiling of Inlet and Exhaust Pipes on the Gas Exchange Processes in Piston Engines

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Abstract

It is known that more than 80% of global energy is produced by internal combustion engines. Therefore, the improvement of working cycles and modernization of systems and components of the piston and combined internal combustion engines with the aim of improving their technical and economic indicators is one of the urgent tasks in the global energy sector. Research studies in this area were carried out mainly by means of numerical simulations or experimentally under static conditions. Information about gas exchange processes in the unsteady gas dynamic conditions are quite limited and controversial. This work aims at obtaining of the additional clarifying information about the gas dynamics in the air-gas tract of the internal combustion engine and finding ways of improving the processes. The results of experimental studies of gas exchange processes in the intake and exhaust tracts piston engines were presented in the article. Experimental studies were conducted on full-scale models of a single-cylinder engine. The experimental dependencies of change of the instantaneous velocity and pressure of the gas flow in the gas paths from the crank angle were presented in the article. Improvement of gas exchange processes in the intake and exhaust pipes of internal combustion engines due to the transverse profiling of the channels was proposed in the paper.

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Keywords: piston engines; gas exchange processe; gas dynamics; flow characteristics; process improvement.

1. Introduction

The efficiency of internal combustion engines largely depends on the efficiency of processes in the intake and exhaust piping [1-3]. The study of gas-dynamic and heat transfer characteristics of gas flow in the air-gas paths been

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given insufficient attention so far. This is due to the fact that the improvement of heat transfer in the cylinder was initially more relevant and effective from the point of view of improving technical and economic performance of piston internal combustion engines (these issues are discussed in a lot of articles in particular [4; 5]). At the moment the engine construction has reached such a level that increasing any parameter of the engine at least a few tenths of a percent is a significant achievement. So now researchers and engineers are looking for new avenues of improving the working cycles of engines. According to the authors one of such directions is the study and improvement of processes in the intake and exhaust pipes of engines in the conditions of gas-dynamic non-stationarity. It is known that the intake and exhaust processes in engines are pulsating, high-frequency and non-stationary. Thus, the study of gas-dynamic and heat transfer characteristics of gas flow in the air-gas paths only in stationary conditions and/or quasi-stationary numerical modeling approaches is not entirely correct. Since, it is known that the parameters of gas flows in the transient conditions may differ from the stationary case in 2-4 times [6-12]. The results of a comprehensive experimental study of gas-dynamic characteristics of gas flows during the intake and exhaust processes in the engine of 8.2/7.1 are presented in this article. Directions of improvement of these processes on the basis of the cross-profiling of piping are also offered in the article.

Nomenclature

ICE	internal combustion engine
TDC	top dead center
BDC	bottom dead center
φ	crank angle, degrees
n	engine crankshaft rotation frequency, rpm
w_x	local speed of gas flow, m/s
V_x	local volumetric gas flow rate, m^3/s
d	channel diameter, mm
l_x	linear dimension, mm

2. Experimental setups and measurement equipments

Experimental setup for experimental investigations of gas-dynamics of the inlet and exhaust processes were designed and manufactured. They were full-scale model of single-cylinder engine of 8.2/7.1. The valve control mechanism for the experimental setups is taken from the engine of the car VAZ-OKA. Valve timing and valve lift of the experimental setups consistent with those for this engine. The drive of a crankshaft was carried out by using an asynchronous motor, the rotational speed of which was regulated by the frequency Converter in the range from 600 to 3000 rpm. A detailed description of the experimental facilities is presented in articles [13, 14].

To make the necessary measurements on the basis of the analog-to-digital Converter was created an automated data collection system, which passed the experimental data in the personal computer. To determine the speed of the air flow (w) and local heat transfer coefficient (α_x) was used constant temperature anemometer [15]. Sensor probes in both cases was the nichrome filament diameter of 5 μm and a length of 5 mm. Measuring speed and position of the crankshaft of the engine produced by the tachometer. It included a toothed disk on the crankshaft and an inductive sensor. These data also determined the position of the upper and lower dead points. The pressure sensor (manufacturer WIKA) was used to measure the instantaneous static pressure of the gas flow.

3. Gas dynamic and flow characteristics of the intake process

Traditionally channels with a circular cross-sectional shape are used in the air-gas paths of engine to provide a uniform velocity field. However it is known that in channels deprived of full symmetry have persistent, longitudinal eddy currents [16]. On this basis it has been suggested that they may affect the dynamics and flow characteristics in the intake and exhaust pipes of the engine. Thus it has been hypothesized that cross-profiling of inlet and exhaust pipes can serve as one method of process improvement in air-gas paths of the internal combustion engines.

Channels with a cross-section in the shape of a circle, square and equilateral triangle were used in this study to verify this hypothesis. A profiled section made up approximately 30 % of the total length of gas-air paths. The equivalent (hydraulic) diameter $d_э$ was equal to 32 mm for the inlet pipe and for the exhaust pipe – 30 mm.

It was found (Fig. 1) that strong oscillatory phenomena after the closing of the intake valve (completion of the intake process) are observed. In this case more rapid damping of oscillatory phenomena is observed when using profiled sections in the air-gas paths. According to the authors, this is due to the stabilizing effect of the longitudinal vortex structures generated at the corners of triangular and square profiles.

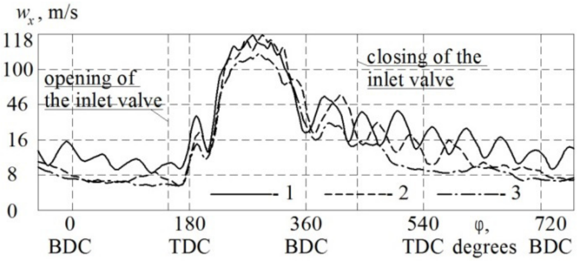

Fig. 1. The dependences of the local (l_x = 110 mm, d = 32 mm) velocity of the fresh charge w_x in the inlet pipes of different cross-section from the crankshaft rotation angle φ for the rotational speed n = 3000 rpm
Cross section shape: 1 – circle; 2 – square; 3 – triangle

The cross-profiling of gas-air paths has an impact on the flow characteristics through the intake system (Fig. 2).

It was found (Fig. 2) that due to the placement of the profiled sections in the inlet pipe can have a number of advantages in comparison with a pipe of circular cross-section. In particular, there are an increase of the volumetric flow of fresh charge through the intake system (in average 22 %) and the increase of the slope of the dependence of the flow of fresh charge from the crankshaft rotation speed in the operating range n when using the "triangular" section. This will lead to increase in power and throttle response of the engine.

The use of "square" section (Fig. 2) leads to a linearization of the flow characteristic via the inlet system in the whole range of the crankshaft rotation frequencies [17].

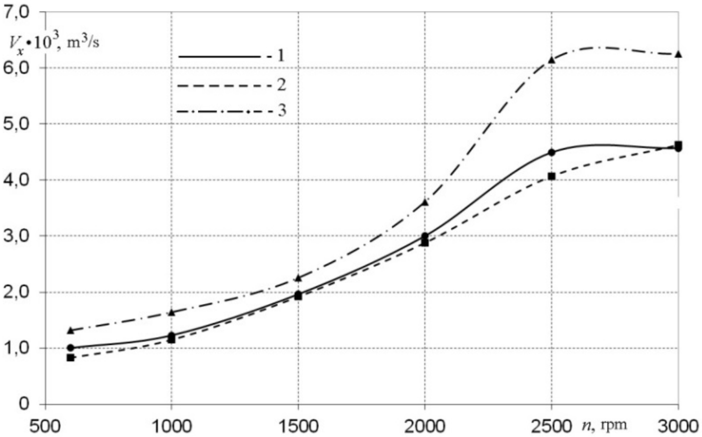

Fig. 2. The dependences of the local volumetric flow of fresh charge V_x through the inlet pipes with different cross-sections from the rotational speed of the crankshaft n
Cross section shape: 1 – circle; 2 – square; 3 – triangle

4. Gas dynamic and flow characteristics of the exhaust process

Study of the exhaust process was carried out for different rotation crankshaft frequencies (from 600 to 3000 rpm) at different excess pressures in the exhaust process (from 0.05 to 0.2 MPa) without the use of a silencer

The dependence of the w_x function of crank angle φ for different configurations of the exhaust system when the rotational speed of a crankshaft n = 1500 rpm is shown in Fig. 3.

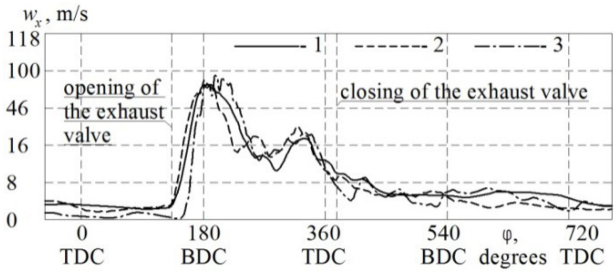

Fig. 3. The dependences of the local (l_x = 140 mm, d = 30 mm) velocity of the gas flow w_x in the exhaust pipes of different cross-section from the crankshaft rotation angle φ at an initial excess pressure p_b = 0,2 MPa and for the rotational speed n = 1500 rpm
Cross section shape: 1 – circle; 2 – square; 3 – triangle

It is established that pulsations of the exhaust gases is most pronounced at low crankshaft rotation frequencies in all configurations of the exhaust pipe. After closing of the exhaust valve the gas flow rate is not equal to zero and there are some rate fluctuations.

Dependences of the local volumetric flow V_x through the exhaust pipe of different geometric shapes from the engine speed n were obtained by processing the graphs of the gas flow rate for a particular engine cycle. The experimental points depending $V_x = f\,(n)$ for different constant excess pressure before the valve are shown in Fig. 4 (dependencies are approximated by linear functions).

Three typical phase diagrams can be provided for the exhaust pipe with a circular cross-section: I - section of the gas flow rate increase (from 600 to 1500 rpm); II – section of the constant gas flow rate (from 1500 to 2600 rpm); III – section of the recession (from 2600 rpm). Reduction of exhaust gas flow at high frequency rotations of the crankshaft is associated with the formation of these modes of stagnant areas in the outlet conduit and the reduction of gas-dynamic flow section [1, 2].

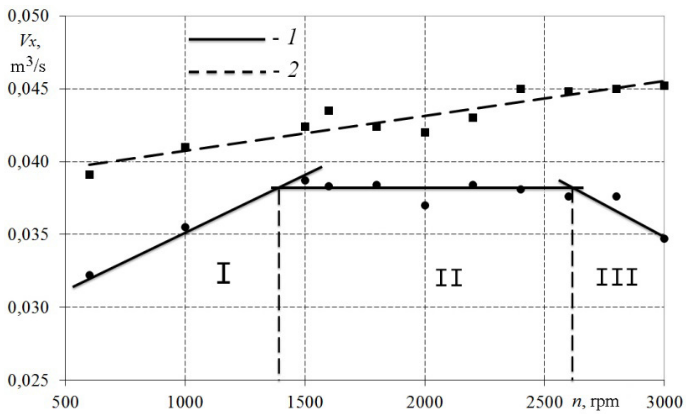

Fig. 4. The dependences of the local volumetric flow of gases V_x through the exhaust pipes with different cross-sections from the rotational speed of the crankshaft n at an initial excess pressure p_b = 0,1 MPa
Cross section shape: 1 – circle; 2 – square

It should be noted that in accordance with the literature data and calculation in the software package "Diesel-RK" the gas flow rate through the exhaust piping monotonically increases with the rotational speed [18]. This continuous growth is due to the increase in the real engine intracyclic pressure in the exhaust process, which leads to a decrease in engine specific work.

Processing of experimental data for exhaust pipe with square cross section under conditions of constant pressure p_b showed that in this case the flow rate increases linearly with increase of the crankshaft rotation frequency. In this case volumetric flow rate of air through the "square" exhaust pipe is greater on average by 25 % compared with a cylindrical pipe [19]. Perhaps the discussed effect is due to the stabilizing effect of the turbulent vortex structures formed in the corners of the square channel.

The increased volume flow of gas through the exhaust system with a profiled section with a cross-section in the shape of an equilateral triangle is observed in the whole investigated range of the crankshaft rotation frequency (Fig. 5). The increase of the flow characteristics through exhaust system with a profiled section will lead to the fact that will improve cylinder scavenging from exhaust gases that in the long term will lead to an increase in engine power over the whole range of modes.

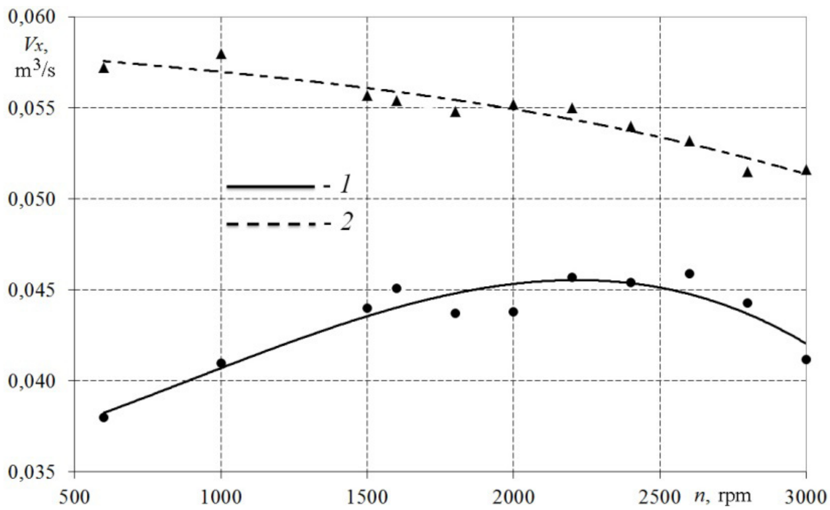

Fig. 5. The dependences of the local volumetric flow of gases V_x through the exhaust pipes with different cross-sections from the rotational speed of the crankshaft n at an initial excess pressure p_b = 0,2 MPa
Cross section shape: 1 – circle; 2 – triangle

It should be noted that when determining the optimal geometric characteristics of the intake and exhaust systems of the engines (including the length and location of the profiled sections) should take into account the specifics of turbulent structures [20]. However, the positive effect achieved by using profiled sections can be determined only on the basis of experimental studies in the modernization of the specific internal combustion engine.

Summary

The following main conclusions can be formulated on the basis of the conducted researches.

1. The influence of rotational speed of the crankshaft and the configuration of inlet and exhaust piping to their gas-dynamic and flow characteristics were established;

2. The frequency and amplitude of changes of the instantaneous values of velocity and pressure in non-steady gas flow for a piston engine were identified;

3. It was found that due to the placement of the profiled sections (with the cross-section in the shape of a square or an equilateral triangle) in the intake pipe can have a number of advantages in comparison with a pipe of circular cross-section:

- increase (by 20% on average) of the volumetric air flow through the inlet system; this will increase the filling ratio and the power of the engine;
- increase in the steepness of the dependence of air flow from the rotational speed of the crankshaft in the working range of n; this will increase the responsiveness of the engine
- the linearization of the flow characteristic over the entire range of the crankshaft rotation frequencies; this will allow to have a more uniform mechanical load on the main parts of the ICE.

4. The cross-profiling of exhaust pipe also leads to a number of advantages:

- the increase in the volumetric gas flow through the exhaust system (average 20 %) compared with pipe of circular cross-section; this will lead to a better cleaning of the cylinder from exhaust gases and improving its efficiency;
- monotonous linear growth of the flow characteristic with increasing crankshaft rotation frequency; this will also lead to improved purification of exhaust gases from cylinders on the main engine operating conditions

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