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Influence of channels transverse profiling on the heat transfer intensity in the intake system of internal combustion engine

L V Plotnikov and M O Misnik

Ural Federal University named after the first President of Russia B.N.Yeltsin, Mira str. 19, Ekaterinburg 620002, Russia

E-mail: plotnikovlv@mail.ru

Abstract. Gas-dynamic perfection and intensity of heat exchange of intake systems determine the efficiency of the piston engine. The results of numerical simulation and experimental study of the heat transfer of gas streams in the intake system of engines having different configurations are presented in the article. Methods of modeling, experimental setup, geometric configuration of pipelines and measuring base are described in the paper. The investigations were carried out under steady-state air flow in the system. The results of mathematical modeling were verified using experimental studies. It is established that the use of profiled sections in the intake system leads to a decrease in the heat transfer rate up to 20 % at low air flow rates (up to 40 m/s) and an increase in the heat transfer rate up to 9 % at high speeds.

1. Introduction

It is known that the intensity of heat exchange in the intake system affects a large number of parameters of the piston internal combustion engine (ICE), such as the level of heating of the working fluid during the intake, the temperature stresses in the parts and components, the value of the filling coefficient, as well as the power and environmental characteristics of the ICE. A large number of studies have been carried out on this topic, among which one can single out the works connected with the study of heat transfer in gas-air systems of engines with supercharged [1-3], the development of mathematical models of processes in the intake system and their verification [4-6], the improvement of the design of intake and exhaust systems of ICEs [7, 8]. Also, this topic is considered in the monographs devoted to the calculation and design of piston and combined engines [9-12]. Therefore, the development of methods to control the heat exchange intensity between the flow of the working fluid and the elements of the intake engine system is an urgent task of the development of engine building. At the same time, it is known that improving the configuration of the intake pipeline causes a change in the gas dynamics and flow patterns in the system [11, 12], and this should lead to a change in the intensity of heat transfer.

This article presents the results of numerical simulation and experimental study of the heat transfer of gas flows in the intake pipelines of internal combustion engines. Intake pipelines had different cross-sections in the studies.

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2. Statement of the research task

It is known that the cross-section of the pipeline channel has a significant effect on gas dynamics and the structure of the gas flow [13]. In this paper, studies were carried out for hydraulic systems with the configurations and boundary conditions typical of the intake systems of piston ICEs. The investigated intake system included a pipeline, an intake valve and a cylinder. The initial base was the intake system, which had channels of constant circular cross-section (figure 1, *a*). In this case, a part of the pipeline (about 30% of the total length of the system) was replaced by a profiled section with a cross-section in the form of a square or an equilateral triangle (figures 1, *b* and *c*). The internal diameter of the intake pipe was 32 mm. Equivalent hydraulic diameter was also 32 mm in all profiled sections. The total length of the intake system was 0.5 m (without taking into account the dimensions of the cylinder).

The studies were carried out, both with the help of mathematical modeling, and experimentally on a laboratory installation.

A number of mathematical models in the CFD package on the basis of the finite element method were developed for a numerical study of heat exchange during gas flow in an intake system with different pipeline configurations. Dry air with a temperature of 20 ^{o}C was used as a working medium, which moved in turbulent mode at an average speed of 10 to 100 m/s (this approximately corresponds to the crankshaft speed range n = 1000-3000 rpm). The mass flow rate was set at the entrance to the model, the model output was defined as the output under pressure equal to the barometric. The k-ε model of turbulence was used to simulate the turbulent gas flow in the system. The problem was solved in a stationary formulation.

Experimental studies of heat transfer in the intake systems of internal combustion engines were carried out for the configurations presented in figure 1. All the geometric dimensions of the pipelines and the cylinder were identical in numerical simulation and in experimental studies. The experiments were carried out under steady-state conditions of air flow in the intake system. At the same time, the intake valve of the piston engine was fixed in the extreme upper (open) position, and the air movement was created by the exhauster, which sucked air from the cylinder. The average air flow rate in the intake pipeline was varied from 10 to 90 m/s. The air temperature was 18-22 °C.

Three control sections were selected in the test pipeline at distances l_x from the window in the cylinder head equal to 100 mm, 200 mm and 300 mm. Two sensors of the thermo-anemometer were installed in each control section (figure 2). Measurement of the local heat transfer coefficient was carried out consistently in 4 places, spaced from each other at an angle of 90^{o} in each control section. To obtain the heat transfer coefficient of the intake system, the coefficient α_x values for each control section were first averaged. Thus, the mean value of the heat transfer coefficient in the cross section was obtained. Then the α_x values for all control sections were averaged.

To determine the instantaneous airflow velocity w_x and the local heat transfer coefficient α_x, a constant-temperature thermo-anemometer was used.

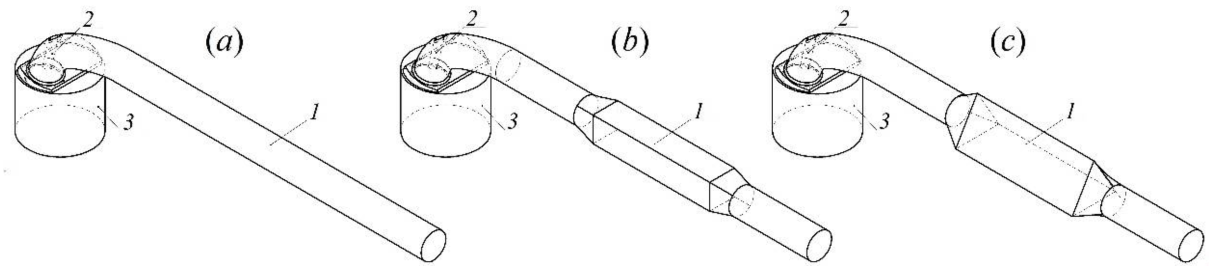

Figure 1. The investigated configuration of the intake system of the piston engine: *1* – intake pipeline; *2* – intake valve; *3* – cylinder. Intake system: *a* – configuration with a pipe with a circular cross section; *b* – configuration with a square section; *c* – with a triangular section.

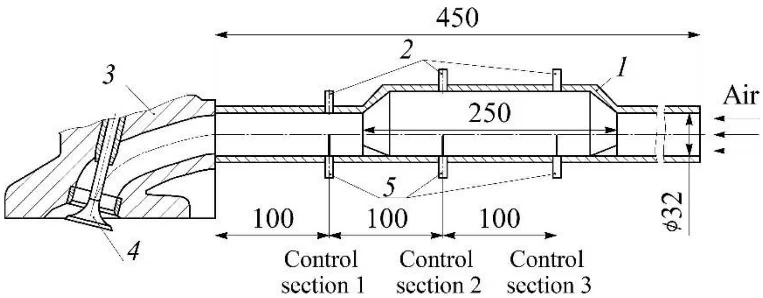

Figure 2. Geometric characteristics of the intake tract and the installation location of the sensors: *1* – profiled intake pipeline; *2* – sensors of a thermo-anemometer for measuring local heat transfer; *3* – cylinder head; *4* – intake valve; *5* – sensors of a thermo-anemometer for measuring local flow velocity.

In our case, the sensitive element of the sensors of the thermo-anemometer was a nichrome thread with a diameter of 5 μm and a length of 5 mm. To measure the air flow velocity, a sensor with a free thread was used, which was placed perpendicular to the axis of the pipeline. To determine the coefficient α_x, a sensor was used with a filament lying on a fluoroplastic substrate that was flush with the wall of the pipeline.

The signals from the thermo-anemometer sensors entered the analog-to-digital converter, which converted the analog signal into a binary code for further processing on a personal computer. The method of determining w_x and α_x is described in more detail in [14].

3. Numerical simulation of heat transfer in the intake system

Numerical simulation was performed to evaluate the influence of the cross-sectional shape of the pipeline on the heat transfer rate in the intake system of the piston engine.

Dependences of heat transfer coefficients α_x on air flow velocity w_x in the intake pipeline with profiled sections with different cross sections are shown in figure 3.

It can be seen from figure 3 that the decrease in the heat transfer rate is observed when using an intake pipeline with a square cross-section at air flow velocities of up to 40 m/s; the reduction reaches 8 % with w_x = 10 m/s (in comparison with the intake system of a constant circular cross-section). The reverse effect is observed with an increase in the flow velocity of above 40 m/s; an increase in the heat transfer intensity by up to 2% is observed under these conditions.

A similar effect was established for the intake system with a profiled section with a triangular cross section. The decrease in the heat transfer rate reaches 14% at air flow velocities of up to 25 m/s (in comparison with the intake system of a constant circular cross-section). The increase in the heat transfer rate up to 5% also occurs in the flow velocity range from 25 to 100 m/s.

Apparently, this phenomenon is associated with a gas-dynamic rearrangement of the flow structure at a velocity of about 20-40 m/s. Further studies of the flow gas-dynamics are needed to explain the effect more clearly.

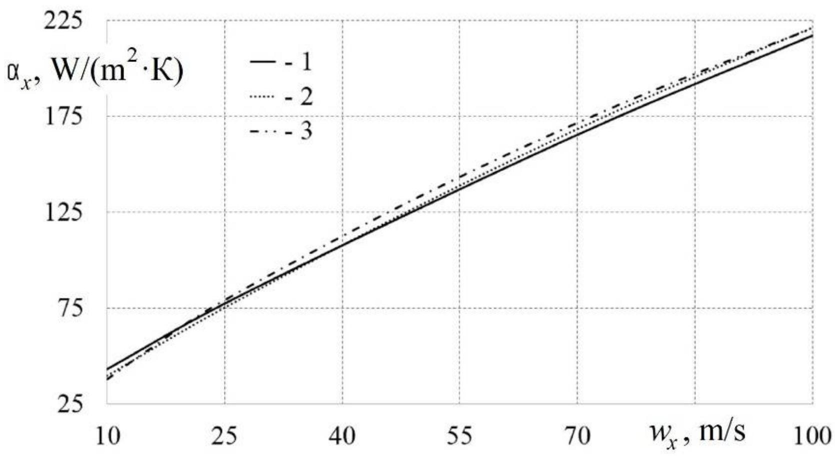

Figure 3. The calculated dependence of the heat transfer coefficient α on the air flow velocity *w* in the intake system with profiled sections with different cross sections: 1 – circle; 2 – square; 3 – triangle.

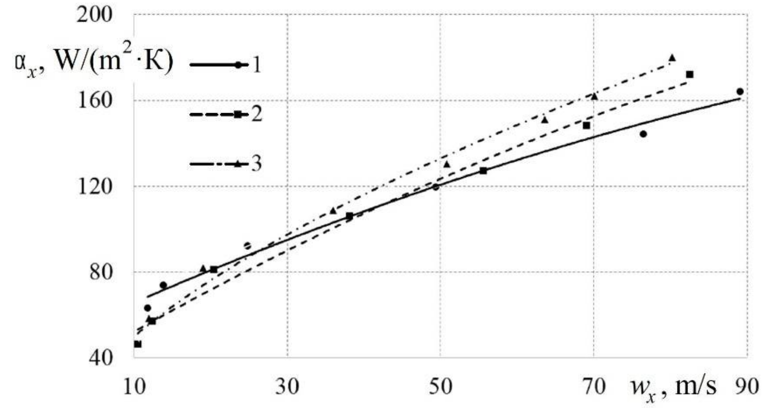

Figure 4. The experimental dependence of the heat transfer coefficient α on the air flow velocity *w* in the intake system with profiled sections with different cross sections: 1 – circle; 2 – square; 3 – triangle.

4. Experimental study of local heat transfer in the intake system

Experimental studies have confirmed the results of numerical simulation at a qualitative level (figure 4). The decrease in the intensity of heat transfer is observed in the intake system of ICEs with profiled sections at low flow velocities of up to 40 m / s (in comparison with the intake system of constant circular cross-section). The reverse effect occurs at high flow rates: there is an increase in the heat transfer coefficient.

Experiments have shown that the reduction of heat transfer intensity is up to 25% when using the intake system with a square cross-section pipeline at air flow velocities of up to 40 m/s as compared with the basic intake system. The increase in heat transfer rate by up to 5 % occurs when the flow velocity exceeds 40 m/s.

Similar data were obtained with the use of an intake pipeline with a triangular cross-section. The decrease in the heat transfer intensity is observed at air flow velocities of up to 25 m/s, which reaches 22 % at w_x = 10 m/s in comparison with the intake system of a constant circular cross section. Conversely, an increase in the heat transfer intensity by up to 9% occurs with an increase in the flow velocity of above 25 m/s.

It is noteworthy that a decrease in the coefficient α_x is observed in all engine modes (i.e. at all crankshaft speeds) when investigating the local heat transfer of pulsating flows in the intake system [15, 16].

5. Conclusions

Thus, numerical modeling and experimental studies have shown that the use of profiled sections in the intake system of the piston engine leads to a decrease (up to 22%) in the heat transfer intensity at low flow rates (at low crankshaft rotation frequencies of ICE); this will contribute to better cylinder filling in these modes. Conversely, the use of profiled sections in the intake system of the piston engine leads to a slight increase (up to 9 %) in the heat transfer intensity at high crankshaft rotation frequencies; this will improve the fuel vaporization and, accordingly, will allow a more homogeneous fuel-air mixture in the combustion chamber of the piston engine.

Acknowledgments

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