Processes Dynamic Characteristics in the Intake System of Piston Internal Combustion Engine

L. V. Plotnikov and Yu. M. Brodov

Abstract The experimental studies of gas dynamic and heat exchange characteristics of processes in the intake system were carried out on the full-scale model of a piston engine. The experimental setup and the instrumentation and measurement base for this study are briefly described. The experimental data on the dynamics of changes in airflow velocity and instantaneous local heat transfer in the intake system of a piston engine are presented in the article. The amplitude–frequency analysis of the considered flow parameters is carried out. It is shown that the intensity of local heat transfer in the intake system in a pulsating flow is much lower than for a stationary flow, and this difference reaches 2.5 times.

Keywords Piston internal combustion engine · Intake system · Gas dynamics Local heat transfer · Pulsating flow · Stationary flow

1 Introduction

Research works of many authors are devoted to the study of processes in the intake systems of piston internal combustion engines (ICE) [1–5]. However, these studies were carried out mainly by numerical simulations of processes in quasi-stationary conditions or experimentally in static modes by blowing of gas–air systems of piston ICEs. The results of modeling are verified on the basis of experimental studies only in some works [6–8].

At the same time, the intake process is a high-speed, highly dynamic phenomenon in a piston engine, and unsteadiness can have a strong influence on its thermogas dynamic characteristics. Therefore, this process is methodically correct to study in dynamics, considering the results of static blowing and mathematical modeling as evaluative.

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A. A. Radionov et al. (eds.), *Proceedings of the 4th International Conference on Industrial Engineering*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-3-319-95630-5_2

2 Experimental Setup and Measuring Instruments

The studies were carried out on the full-scale model of a single-cylinder internal combustion engine of dimension 8.2/7.1 (cylinder diameter is 82 mm, piston stroke is 71 mm) in order to determine the dynamic parameters of the intake process in piston ICEs. The crankshaft of the experimental setup was rotated with an asynchronous motor whose rotational speed was controlled by a Schneider electric frequency converter in the range n = 600–3000 rpm with an accuracy of ±0.1%. A more detailed description of the experimental setup is presented in the monograph [9].

To perform the necessary measurements, the automated measuring system was created on the basis of the L-Card analog–digital converter, which transmits the experimental data to the computer. The anemometer of the constant temperature of the original design (containing a block for protecting the filament from overheating) was used to determine both the air flow velocity w_x and the instantaneous local heat transfer coefficient α_x [10]. The sensitive element of the thermo-anemometer sensors in both cases was a nichrome filament with a diameter of 5 μm and a length of 5 mm. A sensor with a free filament placed on the axis of the intake channel was used to measure the airflow velocity. The sensor with the filament lying on the fluoroplastic substrate was used to determine the coefficient of heat transfer α_x, which was mounted flush with the wall of the intake channel. A more detailed description of the procedure for determining the local heat transfer coefficient is described in the paper [11]. The systematic error in measuring the flow rate w_x was 5.4%, and the local heat transfer coefficient was 10%. See also [9, 11]. Experiments on the measurement of the coefficient α_x were carried out both in the stationary mode of air movement (the intake valve was opened; the air movement was created by a special exhauster sucking the air from the cylinder) and the pulsating regime (under conditions of gas dynamic unsteadiness). The measurement of the speed and indication of the passage of the top dead center (TDC) and the bottom dead center (BDC) were performed by a tachometer consisting of a toothed disk fixed to the shaft and an inductive sensor.

Prior to considering the problem, it should be noted that there is virtually no data on the dynamic characteristics of the intake process. Therefore, it was methodologically advisable to begin studying the problem from the simplest intake channel (up to the cylinder head). Thus, the results of the investigation for a straight channel with a circular cross-section without an air filter are discussed in this article.

The configuration of the working section of the intake system and the location of the sensors of the thermo-anemometer for measuring the air flow velocity w_x and the local heat transfer coefficient α_x are shown in Fig. 1.

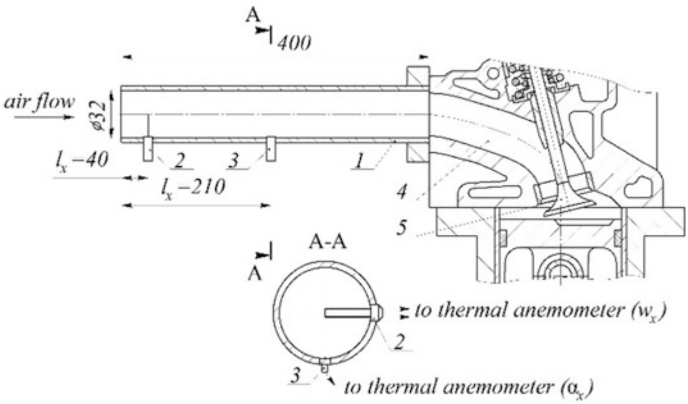

Fig. 1 Configuration of the intake path of the experimental setup: 1—straight pipe; 2—sensor of a thermo-anemometer for measuring air flow velocity; 3—thermal anemometer sensor for determining the local heat transfer coefficient; 4—curved channel in the cylinder head; 5—intake valve

3 Gas Dynamics of the Intake Process

It was found that the dynamics of the intake process becomes more complicated with an increase in the crankshaft rotational speed (Fig. 2), i.e., the complexity of the dependence of the flow velocity in the intake pipe increases. The airflow rate w_x in the intake pipe rises with increasing speed of the crankshaft and reaches about 100 m/s. Simultaneously, the influence of pulsation effects is enhanced. See also [12, 13].

At the maximum frequencies of the crankshaft (Fig. 2b), the intake process begins when there are intense transients in the intake pipe; this can adversely affect the process of filling the cylinder. At low rotational frequencies (Fig. 2a), it begins practically from the steady state. Strong oscillatory phenomena are observed after the intake valve is closed (the intake process is completed). Fluctuations of the air flow in the intake pipe are retained until the beginning of the next intake process at high n. It is noteworthy that the extremum of the flow velocity in the intake channel, fixed by the sensor far from the entrance to the measuring channel, can outrun the speed extremum from the proximity sensor; this indicates the presence of a return flow in the system (Fig. 2b, regions A and B).

This phenomenon is explained by the fact that the gas flow, moving by inertia, is reflected from the closed intake valve and starts to move in the opposite direction. At the same time, a vacuum area arises near the valve, which causes the flow to return back with subsequent re-reflection, and then this process of wave motion occurs until the energy of the flow is consumed. Dissipative process has time to develop sufficiently at low speeds of the crankshaft, and a new intake process occurs practically from the stationary state. The dissipation does not have time to finish at high speeds of the crankshaft and the oscillatory phenomena remain until

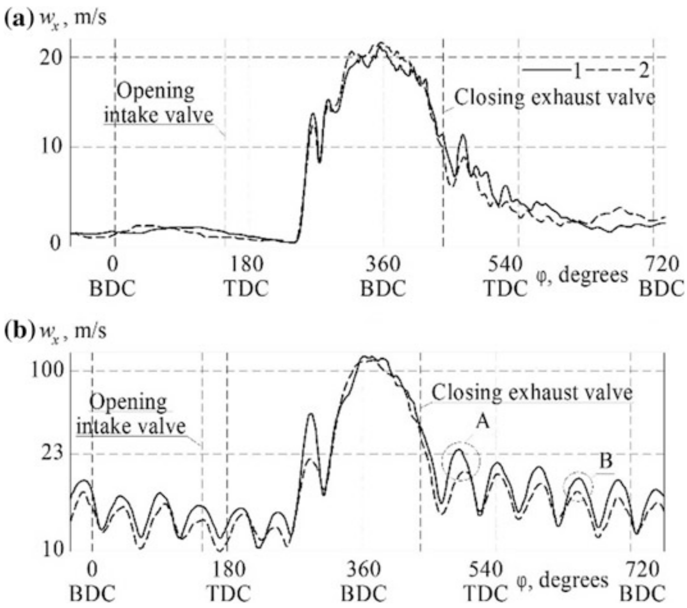

Fig. 2 Dependence of the airspeed w_x in the intake pipe of the piston engine from the crankshaft rotation angle φ at different frequencies of the crankshaft n: **a** n = 600 rpm; **b** n = 3000 rpm; 1—the signal from the first during the flow thermo-anemometer; 2—the signal from the second anemometer

the next intake process. The considered oscillatory phenomena are similar to those that occur during the exhaust process, as shown in [14–17].

The ability of air charge (air flow) to ensure efficient mixture formation is one of the most important factors determining the performance of an internal combustion engine. The mixture formation process is largely determined by the magnitude of the heating of the air charge (air flow) and the intensity of turbulent pulsations that are formed in the intake system of the piston ICE. Information about this can be obtained by amplitude–frequency analysis of velocity pulsations and the local heat transfer coefficient of the flow in the intake system. An analysis of the pulsation spectrum of the air flow velocity w_x in the intake system, obtained with the help of the fast Fourier transform algorithm, was carried out in this study (Fig. 3).

Four multiples of the frequency spectrum, 6.0, 12.0, 18.0, and 24.0 Hz, are clearly expressed in the lower part of the spectrum at a rotational speed of the crankshaft equal to 600 rpm (Fig. 3a); it should be noted that there is no process frequency f_{pr}, which is 10 Hz. Pulsations of high-frequency $f > 30$ Hz are practically insignificant (at n = 600 rpm). Four frequencies, 25.0, 50.0, 75.0, and 100 Hz, are manifested as the main energy significance at the maximum crankshaft speed of 3000 rpm (Fig. 3b). At the same time, frequency fluctuations f_{pr} = 50 Hz are expressed for this intake system and this mode of operation, and there are significant high-frequency oscillations extending up to 160 Hz. It is characteristic

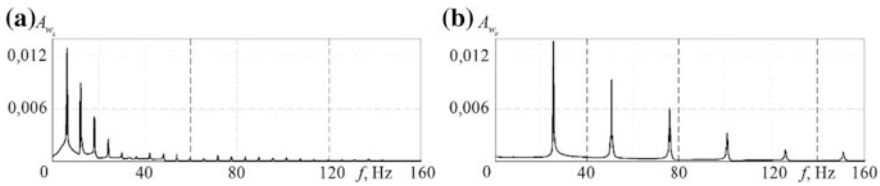

Fig. 3 Spectra of pulsations of the air flow velocity w_x in the intake pipe of the piston engine at different speeds of the crankshaft: **a** n = 600 rpm; **b** n = 3000 rpm

that the maximum spectral density of the signal pulsations has approximately the same value, both at the smallest and at the highest crankshaft rotation frequency.

4 Intensity of Local Heat Transfer in the Intake System

The combined dependences of the air flow rate w_x and the local heat transfer coefficient on the crankshaft rotation angle φ indicate that the dynamics of the change and the intensity of heat transfer depend strongly on the crankshaft rotational speed n (Fig. 4). The heat transfer intensity and maximum values of the coefficient α_x increase with the frequency n. The delay in the change in the heat transfer intensity from the velocity of the air flow along the angle by an amount $\Delta\varphi$ is observed, which depends on the rotational speed of the crankshaft. Thus, the angle lag $\Delta\varphi$ is 50° in the range $600 < n < 1500$ rpm, while it decreases to 30° at n = 3000 rpm. Apparently, this indicates that active turbulent structures are formed in the boundary layer from $n \approx 1500$ rpm; accordingly, heat exchange begins to react more quickly to a change in the hydrodynamic situation.

It is established that a noticeable rise in the coefficient α_x begins at approximately the same crankshaft rotation angle ($275 < \varphi < 280$) at all frequencies n and in all control sections. And the maximum values of the heat transfer coefficient also reach in a single range ($375 < \varphi < 420$). Variations of instantaneous local heat transfer coefficient are virtually extinguished at $\varphi \approx 720°$; this is probably due to the damping effect of a viscous sublayer. All this testifies to the general regularity of the change in the coefficient α_x from the angle φ in the intake system of the piston engine at all crankshaft speeds. See also [18].

The pulsation spectrum of the local heat transfer coefficient α_x in the intake system of a piston engine is shown in Fig. 5. The first four frequencies of the spectrum, 6.0, 12.0, 18.0, and 24.0 Hz, are clearly expressed at low crankshaft frequencies (Fig. 5a). Similar data were obtained for the air flow velocity spectrum (see Fig. 3a). Significant spectrum frequencies are virtually absent in the range of more than 30 Hz. The same pattern is maintained at the maximum speed of the crankshaft (Fig. 5b). The first four frequencies, 25.0, 50.0, 75.0, and 100.0 Hz, can be identified as the main energy importance. In addition, significant high-frequency

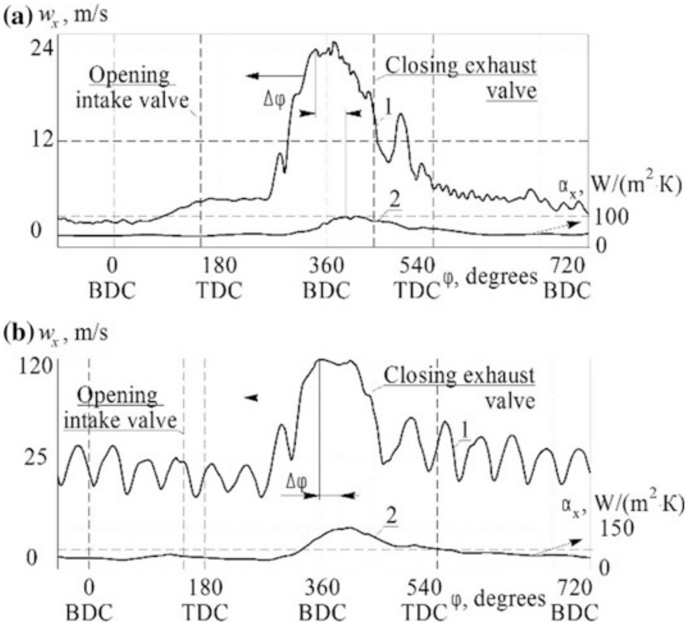

Fig. 4 Dependences of the air flow rate w_x (1) and the local (l_x = 110 mm) heat transfer coefficient α_x (2) on the crankshaft rotation angle in the intake pipe of the piston engine at different speeds of the crankshaft: **a** n = 600 rpm; **b** n = 3000 rpm

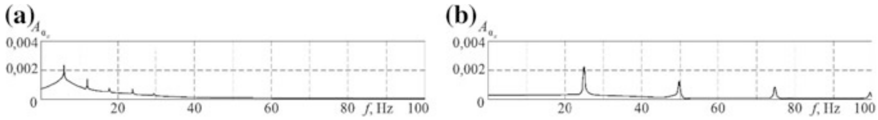

Fig. 5 Spectra of local (l_x = 110 mm) heat transfer coefficient pulsations in the intake pipe of the piston engine at different speeds of the crankshaft: **a** n = 600 rpm; **b** n = 3000 rpm

oscillations in the range up to 100 Hz are observed for this configuration of the intake system. At the same time, the technological frequency f_t = 50 Hz is clearly pronounced.

The combined amplitude–frequency characteristics are shown in Fig. 6 for comparing the structure of the pulsations spectra of w_x and α_x.

The main frequencies of the pulsation spectra of the velocity and the local heat transfer coefficient approximately coincide at all crankshaft speeds. This indicates a significant effect of the flow dynamics on heat transfer and the absence of natural oscillations in the viscous sublayer on the walls of the intake pipe. At the same time, significant high-frequency components (f > 100 Hz) are observed in the pulsation spectrum of the air flow velocity in the considered intake manifold of the piston ICE; this indicates the presence in the flow of small-scale, stable turbulent

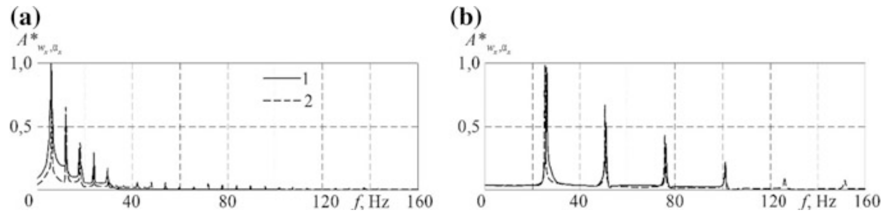

Fig. 6 Spectra of pulsations of the air flow velocity w_x and local (l_x = 110 mm) heat transfer coefficient α_x in the intake pipe of the piston engine at different speeds of the crankshaft: **a** n = 600 rpm; **b** n = 3000 rpm

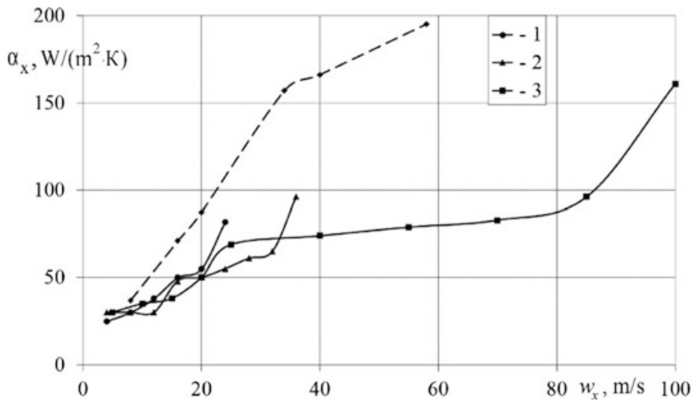

Fig. 7 Dependence of local (l_x = 110 mm) heat transfer coefficient α_x on airflow velocity w_x under different hydrodynamic conditions: 1—n = 600 rpm; 2—n = 1500 rpm; 3—n = 3000 rpm; ——— stationary flow; —— pulsating flow

structures. It is known that large-scale turbulent flow of air has a positive effect on the process of mixture formation, whereas the presence of small-scale turbulence can lead to a re-swirling of the air flow, which worsens the formation of mixtures.

Let us consider the dependence of the instantaneous local heat transfer coefficient α_x on air flow velocity w_x under different experimental conditions (Fig. 7) in order to demonstrate significant differences in the parameters of heat exchange processes during static blowing and pulsating mode in the intake system of piston ICEs.

Experiments have shown that there is a significant difference in the values of the local heat transfer coefficient in the stationary and dynamic flow regimes at the same flow rate. It is established that gas dynamic unsteadiness leads to a strong decrease of heat transfer in the intake system, which can reach 2.5 times in comparison with the steady-state flow. Similar results were also obtained in the works of other authors [19–21].

5 Conclusion

Experimental studies on the instantaneous values of the air flow velocity and the local heat transfer coefficient were carried out on a single-cylinder piston engine.

Spectral analysis of pulsations of air flow velocity and local heat transfer coefficient was performed for the intake system of the piston ICE.

It is established that gas dynamic nonstationarity leads to a decrease in the intensity of heat transfer by approximately 2.5 times in comparison with the stationary flow of air in the intake system.

It can be concluded that the results of nonstationary experiments and special empirical equations describing the dynamics of the intake process in piston ICE should be used to perform correct calculations of gas dynamics and heat transfer in the intake system.

Acknowledgements The work has been supported by the Russian Science Foundation 18-79-10003.

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