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THE CHARACTERISTIC FEATURES OF GAS DYNAMICS AND HEAT TRANSFER OF STATIONARY AND PULSATING FLOWS IN THE INTAKE SYSTEM OF A PISTON ENGINE

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Data on gas dynamics and heat transfer of stationary and pulsating flows along the length of the intake system of a piston engine are presented. The studies were carried out on full-scale models of a piston engine for different initial conditions. The influence of gas-dynamical nonstationarity on the thermal-mechanical characteristics of flows is shown experimentally. It has been established that the degree of turbulence of pulsating flows is an order of magnitude higher than in a stationary flow, and the intensity of heat emission, on the contrary, is 5–13% less. It is shown that the values of the degree of turbulence tend to decrease (up to 2 times) when air moves along the length of the intake system, and the change in the intensity of heat emission has a parabolic form, which is typical of both stationary and pulsating flows. The results obtained can be used for refining engineering methods of calculating the processes of gas exchange and developing the means of improving the intake systems of piston and composite engines.

Keywords: *piston engine, intake system, gas flows, gas dynamics, turbulence degree, local heat emission, comparative analysis.*

Introduction. Requirements for environmental safety and efficiency of internal combustion engines become more stringent every year. The specialists in the field of piston engine building are sure that the potential of internal combustion engines has not been fully exhausted [1]. Therefore the improvement of the working cycle and the design of its systems remains an urgent task in the development of power engineering (about 25% of electrical energy and heat are generated by reciprocating internal combustion engines).

It is known that the intake process, i.e., the process of filling the engine cylinder with a working fluid, largely determines the quality of mixture formation of the fuel–air mixture and its combustion and, accordingly, the uniformity of operation, environmental as well as technical and economic indicators of the engine as a whole [2, 3]. A large number of diverse works are devoted to the study of physical processes and improvement of the design of intake systems. For example, it is possible to single out studies based on physical and mathematical modeling on fine-tuning the elements of the intake system in order to improve the flow-rate characteristics [4, 5]. It has been established that it is possible to achieve an increase in the rate of air flow though the system up to 20% by optimizing the construction of the intake pipes and channels. There are also similar experimental works, which show that the modernization of the intake system configuration leads to an increase in the efficiency and power of the engine (up to 15%), as well as to a decrease in emissions of harmful substances [6, 7]. Mention should be made of the works in which a Helmholtz resonator is installed in the intake system to improve the flow rate characteristics (an increase up to 70%) [8], reduction of noise (by 50–60 Hz) [9], increase in the power (up to 6%) and efficiency (within 1%) of the engine [10]. A separate trend in improving the working cycle of the internal combustion engine is to adjust the length, diameter, and cross-sectional shape of the intake system pipelines [11, 12]. There are also other ways of increasing the efficiency of internal combustion engines by improving gas exchange processes, in particular, the use of a pipeline with grooves on the inner surface of the channel [13, 14], the use of electromagnetic valves [15], refinement of gas distribution phases [16], and others. An important feature of the study of thermomechanical processes in the intake system is the consideration of gas-dynamical unsteadiness typical of the piston engine cycles and of vortex formation at the intake and in the cylinder [17–20].

Thus, it can be stated that specialists focus on mathematical simulation and integral evaluation of certain methods for improving engine designs, and at the same time pay little attention to obtaining detailed, experimental data on thermal

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and mechanical characteristics of flows in the processes of gas exchange of internal combustion engines. Accordingly, the main objectives of this study can be formulated as follows:

1) to obtain data on gas-dynamical and heat exchange characteristics for stationary and pulsating flows in a gas-dynamical system, the configuration of which is typical of the intake system of a piston engine;
2) to reveal and analyze differences in gas dynamics and heat transfer for stationary and pulsating regimes of air flow in the intake system under different boundary conditions;
3) to establish laws governing changes in gas-dynamical and heat transfer characteristics along the length of the intake system of an engine for stationary and pulsating flows.

Experimental Installations, Measuring Devices, Methods of Conducting Experiments. Studies of gas dynamics and heat transfer of stationary and pulsating gas flows were carried out on laboratory stands simulating the geometric and physical conditions typical of reciprocating internal combustion engines.

An automobile engine with a piston diameter of 82 mm and a piston stroke of 71 mm was chosen as a prototype. The main geometric dimensions and components were borrowed from this engine. A stationary flow in the intake system was created by producing a vacuum in the cavity–cylinder by using a pump (Fig. 1). In this case, the inlet valve was in a fully open position (valve lift was 10 mm). Studies were carried out for different average air flow velocities w from 10 to 40 m/s, which were created by adjusting the flow rate characteristics of the exhaust pump. The working medium in the experiments was air with a temperature of 20–22^{o}C and a barometric pressure of 0.1 MPa.

To study the gas dynamics and heat transfer of pulsating gas flows in the intake system, a full-scale model of an internal combustion engine was developed, the crankshaft of which was driven by an electric motor (Fig. 2). Thus, in this case, the pulsating regime of air motion in the intake system was created due to the reciprocating movement of the piston in the cylinder of the engine. Accordingly, when the piston moved from top to the bottom dead center, a vacuum was created in the cylinder, and air, which passed from the atmosphere through the intake system, filled the cylinder. The gas distribution phases and the geometric dimensions of the main elements of the installation were borrowed from the prototype, which was the engine from the VAZ-OKA car. In this case, studies were carried out for different crankshaft rotational speeds n — from 600 to 3000 min^{-1} — which corresponds to the average air flow velocities in the intake system w from 10 to 55 m/s. The rotational speed of the crankshaft was regulated by means of a frequency converter with an accuracy of 0.25%.

The configurations of the inlet systems with stationary blowdowns and a pulsating flow were identical (Fig. 3). So, in both cases, the length of the intake pipe was 350 mm, and the total length of the system was about 500 mm. The intake system had 5 control sections located along the entire length. The first section was located at a distance of 50 mm from the system inlet, and the last two sections were in the channel, in the block head and near the valve seat. Locations of sensors and numbers of control sections are shown in Fig. 3.

The general view of the control section is shown in Fig. 4. During the experiments, two key indicators were measured: the local air flow velocity w_x and the local heat emission coefficient α_x. For this, a constant temperature hot-wire anemometer was used.

To determine the instantaneous values of the air flow velocity, a sensor with a filament located approximately in the center of the channel, perpendicular to the oncoming flow, was used. The diameter of the sensing element (filament) was 5 μm and the length was 5 mm. The sensitive element was heated to a temperature of 120^{o}C. The so-called thermal sensor was used to determine the instantaneous values of the local heat emission coefficient. It was a substrate made of fluoroplastic with a thread stretched over its surface (diameter 5 μm, length 5 mm). The substrate was installed flush with the inner surface of inlet pipe. Thus, the sensor measured the local friction stresses, which are related to α_x through the Reynolds analogy [21, 22]. The method of determining the local heat emission coefficient is described in more detail in monograph [23]. The relative uncertainty of measuring the air flow velocity was 5.2% and the local heat emission coefficient was 12%.

When analyzing the gas-dynamical characteristics of air flows in the intake system, two indicators were used: 1) average velocity w and 2) the degree of flow turbulence Tu. The values of Tu for stationary and pulsating flows were calculated as the ratio of the root-mean-square pulsating velocity component to the average velocity of the flow under study [21]. Here, the definition of the average velocity for a stationary flow and a pulsating flow differed significantly. For stationary flows w was calculated as the mathematical expectation of the function $w_x = f(\tau)$, and for a pulsating flow the average velocity was determined using phase averaging over the full cycle of the engine (at least 5 full cycles were taken into account in the calculation).

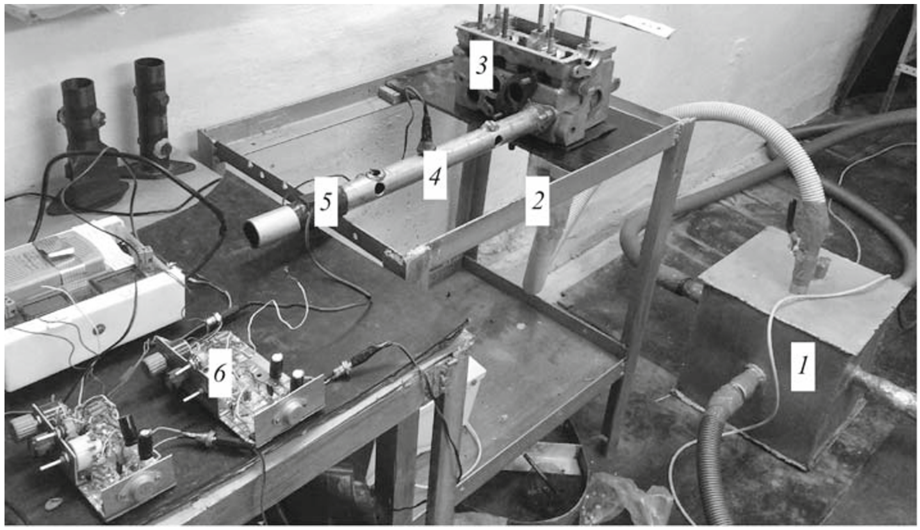

Fig. 1. Scheme of the experimental stand for studying gas dynamics and heat transfer of stationary gas flows: 1) receiver; 2) cavity-cylinder; 3) head of the block with valve mechanism; 4) control section with hot-wire anemometer sensors; 5) inlet pipe; 6) hot-wire anemometers of constant temperature.

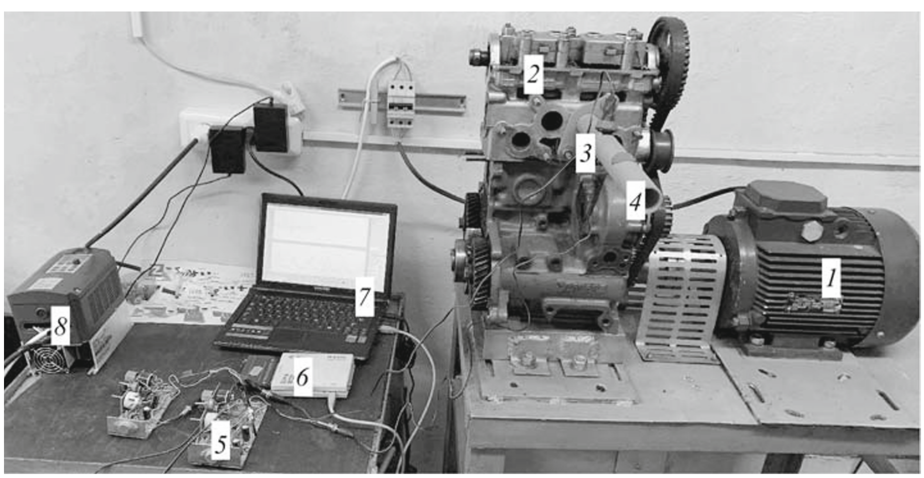

Fig. 2. Experimental stand for studying gas dynamics and heat emission of pulsating gas flows: 1) electric motor; 2) head of the block with a valve mechanism; 3) control section with sensors; 4) inlet pipe; 5) hot-wire anemometer; 6) analog-to-digital converter; 7) notebook; 8) frequency converter.

The averaged heat emission coefficient α was used in analyzing the heat exchange characteristics of air flows in the intake system. For stationary flows, α was defined as the mathematical expectation of the function $\alpha_x = f(\tau)$, and for a pulsating flow α was calculated as the average value of the instantaneous values of the local heat emission coefficient for the period of the intake process (i.e., for the period when the inlet valve is open).

Comparative Analysis of Gas-Dynamical and Heat-Exchange Characteristics of Stationary and Pulsating Flows in the Intake System of an Engine. In Fig. 5 it is shown that in the case of stationary air flow in the intake system, the instantaneous values of the air flow velocity and of the local heat emission coefficient have a chaotic spread in time, which is typical of all control sections. Accordingly, to obtain physical regularities, it is necessary to use integral characteristics (see below).

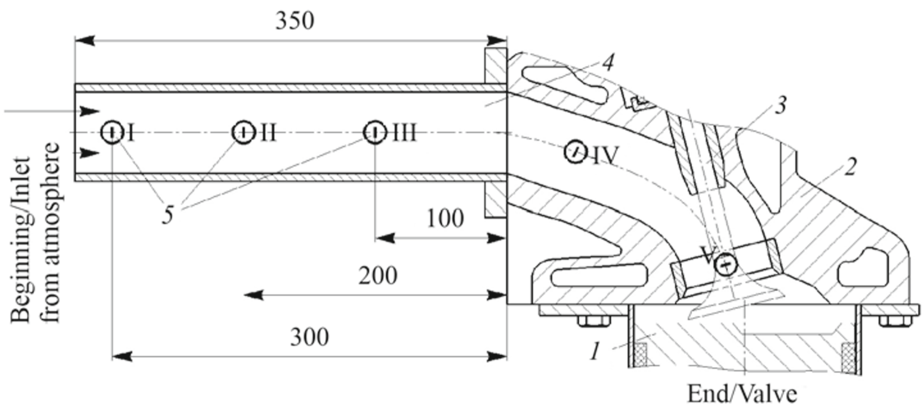

Fig. 3. Configuration of the intake system with indicated locations of sensors: 1) cavity-cylinder; 2) head of the block; 3) inlet valve; 4) inlet pipe; 5) hot-wire anemometer sensors; I–V) control sections for measuring gas-dynamical and heat-exchange characteristics of flows. Dimensions are in mm.

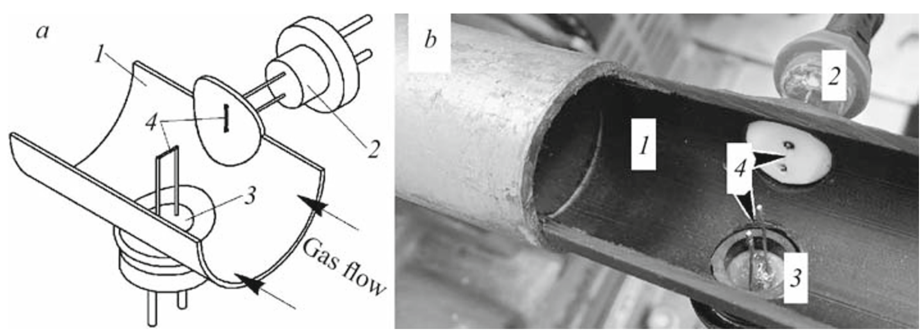

Fig. 4. Scheme (a) and photograph (b) of the location of hot-wire anemometer sensors in the inlet pipe: 1) inlet pipe; 2) hot-wire anemometer sensor for determining the local heat emission coefficient; 3) hot-wire anemometer sensor for determining the local air flow velocity; 4) sensitive element (nichrome thread) of sensors.

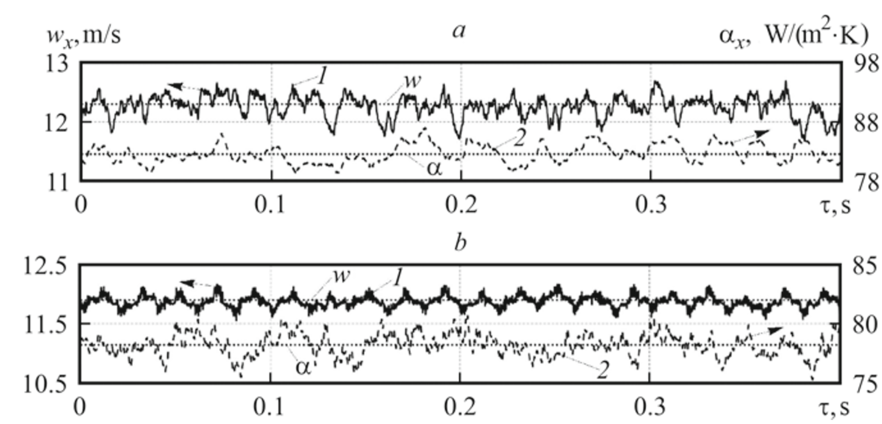

Fig. 5. Local velocity w_x (1) and local heat emission coefficient α_x (2) vs. the time τ for different control sections in the intake system with a stationary air flow: a) section I, w = 12.3 m/s, α = 82.5 W/(m^2·K); b) section IV, w = 11.9 m/s, α = 78.1 W/(m^2·K).

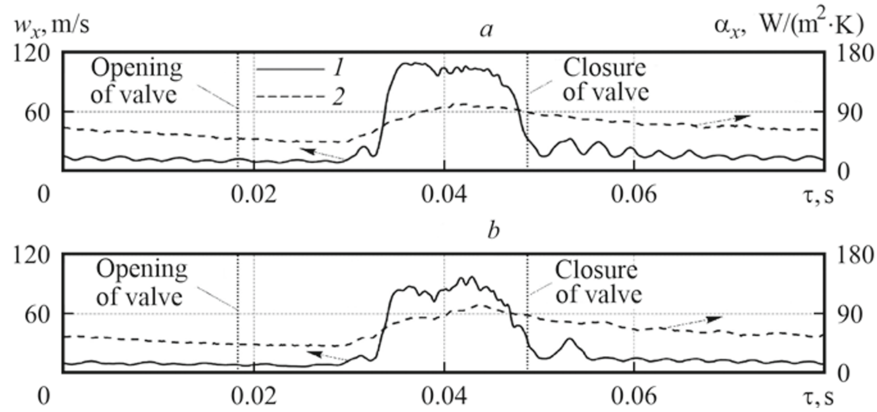

Fig. 6. Local velocity w_x (1) and local heat emission coefficient α_x (2) vs. the time τ for different control sections in the intake system with a pulsating air flow: a) section I, $n = 1500$ min^{-1}; b) section IV, $n = 1500$ min^{-1}

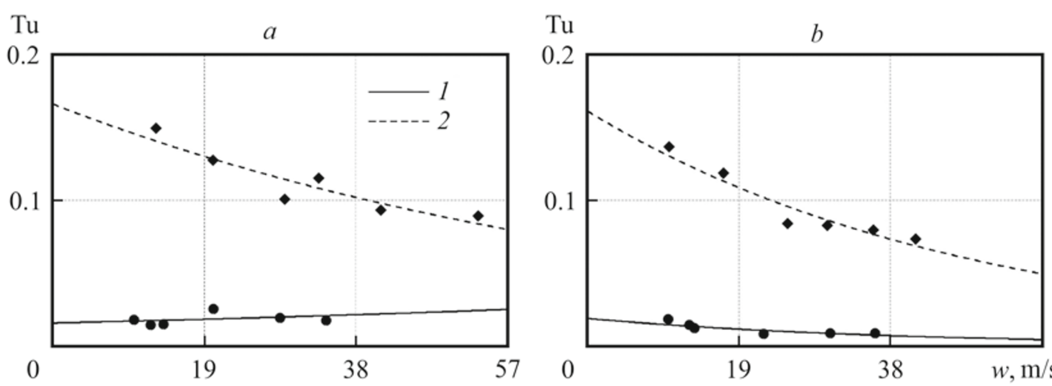

Fig. 7. Degree of turbulence Tu vs. average air flow velocity w in the intake system with stationary (1) and pulsating (2) flow regimes for different control sections: a) section I; b) section IV.

In turn, the pulsating air flow in the intake system of a piston engine has its specific characteristics (Fig. 6). It should be noted that there is a decrease in the maximum values of the downstream air flow velocity within 12% at a constant rotational speed of the crankshaft. On closure of the valve, a reciprocating movement of air with a pronounced damping oscillatory process is observed in the intake system (Fig. 6a). These oscillatory processes are most noticeable in the initial section of the intake system (at the inlet) and are practically absent in the channel in the cylinder head (Fig. 6b). In this case, the dependences $\alpha_x = f(\tau)$ at a constant crankshaft rotational speed do not differ visually along the length of the intake system.

It has been established that in a stationary flow, the degree of flow turbulence is practically a constant value in each individual control section, i.e., the values of Tu actually do not change at all flow velocities studied (Fig. 7). The differences in the values of Tu in different control sections do not exceed 14%, in this case. This can be explained by the fact that the external perturbation does not exert a noticeable effect on the flow, and the presence of the bend in the channel and of an obstacle in the form of a valve does not cause an increase in the pulsating component in a stationary flow.

It was found that the gas-dynamical unsteadiness determines a significant increase in the degree of flow turbulence compared to a stationary flow, which reaches 10 times (Fig. 7).

Accordingly, it can be stated that in a pulsating flow small-scale turbulence arises additionally, which can exert an effect on the heat transfer intensity. In this case, there occurs a decrease in Tu (by 30–45%) in a pulsating flow with an increase in the air flow velocity, which is characteristic for all the control sections under study.

It is shown that in a pulsating flow, the intensity of heat emission is up to 13% lower than in a stationary flow (Fig. 8). In this case, downstream the differences in the averaged heat emission coefficients decrease and do not exceed 5%

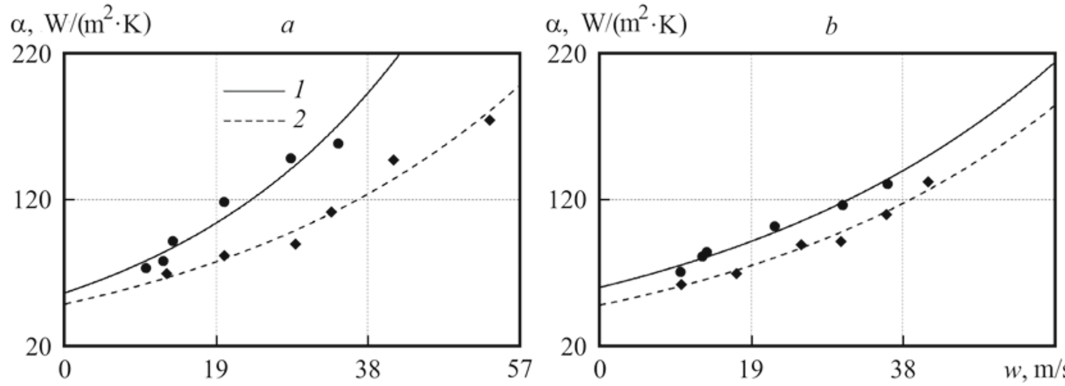

Fig. 8. Averaged heat emission coefficient α vs. average air flow velocity w in the intake system with stationary (1) and pulsating (2) flow regimes for different control sections: a) section I; b) section IV.

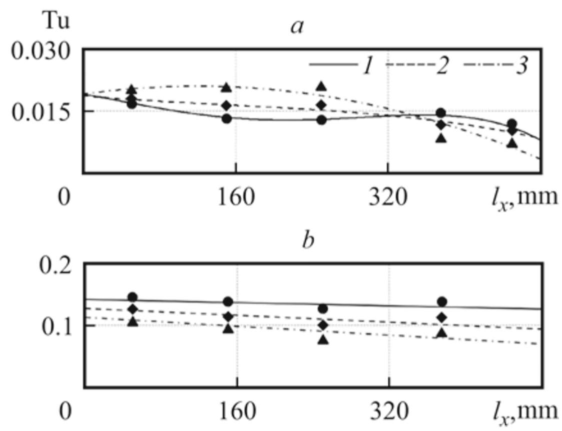

Fig. 9. Degree of turbulence Tu along the length l_x of the intake system with stationary (1) and pulsating (2) flow regimes for different average air flow velocities w: 1) 10 m/s; 2) 20; 3) 30.

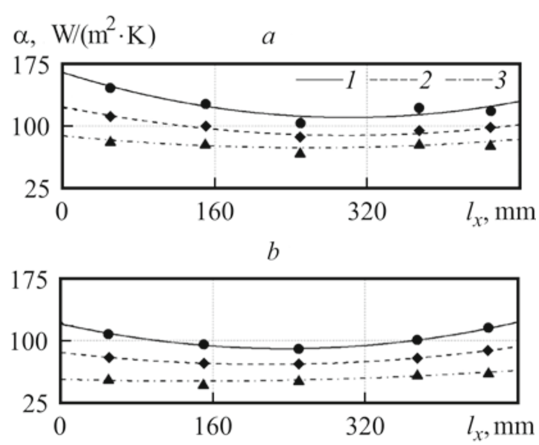

Fig. 10. Averaged heat emission coefficient α along the length l_x of the intake system with stationary (1) and pulsating (2) regimes of flow for different average air flow velocities w: 1) 10 m/s; 2) 20; 3) 30.

in the control section near the valve. It should be noted that a similar trend was also established for the exhaust system of a piston engine [24].

The revealed trends must be taken into account when designing gas exchange systems of piston engines, since they can exert a significant influence on the quality of filling the cylinder with a fuel–air mixture, the processes of mixture formation and combustion, and, accordingly, on the technical, economic, and environmental performance of internal combustion engines.

Next, we will analyze the changes in the gas-dynamical and heat-transfer characteristics of stationary and pulsating flows along the length of the intake system of a piston engine (Figs. 9 and 10). It has been established that in a stationary flow, the degrees of turbulence are in the range from 0.011 to 0.021 and tend to a nonmonotonic (nonlinear) decrease along the length of the intake system (Fig. 9a). This is typical of all the average flow velocities studied. This can be explained by some relaxation of the flow as it moves from the inlet section, where the maximum values of Tu are observed. It was revealed that in the case of pulsating flow the values of the degree of turbulence are in the range from 0.1 to 0.145 and tend to decrease linearly along the length of the intake system (Fig. 9b). This trend is typical of all average flow velocities.

It should be noted that in the exhaust system of a piston engine, opposite physical patterns were observed for stationary and pulsating flows [24]. There, the maximum values of Tu were observed in the area of the valve, which turbulized the flow, and as the flow moved along the exhaust system, the degree of turbulence decreases intensively.

The change in the averaged heat emission coefficient α along the intake system of the engine with stationary and pulsating flows has a parabolic trend (Fig. 10). In both cases, higher values of α are observed at the inlet section of the system, with a slight decrease being observed in the intensity of heat emission, whereas α increases again in the cylinder head in the channel. The high values of the heat emission coefficient in the initial section (at the flow inlet to the pipeline) can be explained by the presence of vortices and the formation of a boundary layer [25]. In turn, the increased values of α in the channel in the cylinder head are explained by the presence of a bend and an obstacle (valve), which lead to a change in the flow structure and a change in the thermal boundary layer.

The data obtained can be useful in designating the intake system of a piston engine for the correct choice of its geometric dimensions (in order to ensure optimal heat transfer conditions), which is especially important for turbocharged internal combustion engines.

CONCLUSIONS

Based on the obtained experimental data and their analysis, the following main conclusions can be drawn:

1. Laboratory stands have been developed that simulate the physical processes occurring in the intake system of a piston engine. Measuring instruments are selected, methods of conducting experiments are determined, which allow obtaining data on gas dynamics and heat emission of stationary and pulsating air flows in the intake system of the internal combustion engine with sufficient reliability.
2. Differences in gas-dynamical and heat-exchange characteristics between stationary and pulsating air flow regimes in the intake system of the internal combustion engine are shown. In particular, it has been established that the degree of turbulence of pulsating flows is an order of magnitude higher than in a stationary flow. In this case, the intensity of heat emission in a pulsating flow is 5–13% less than α for stationary flows.
3. The laws governing the changes in the gas-dynamical and heat-exchange characteristics of stationary and pulsating flows along the length of the intake system of the internal combustion engine have been revealed. For example, it is shown that the values of the degree of turbulence tend to fall (up to 2 times) when air moves through the system under consideration, which is typical of both stationary and pulsating flow regimes. Differences are observed only in the intensity and patterns of decline. In turn, the change in the intensity of heat emission along the length of the intake system has a parabolic form, which is also typical of the all studied regimes and velocities of air flows.
4. The obtained data and established regularities expand the theoretical base in the field of gas dynamics and heat transfer of air flows in gas-dynamical systems of complex configuration. In the applied aspect, these results can be used in engineering calculations and in the design of gas exchange systems of piston engines with and without turbocharging.

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NOTATION

d, channel diameter, m; l, linear dimension, mm; n, rotational frequency of the crankshaft of an engine, $\min^{-1}$; Tu, degree of flow turbulence; w_x, local air flow velocity, m/s; w, averaged air flow velocity, m/s; α_x, local heat emission coefficient, $W/(m^2 \cdot K)$; α, averaged heat emission coefficient, $W/(m^2 \cdot K)$; τ, time, s. Index: x, local parameter.

REFERENCES

1. R. D. Reitz, H. Ogawa, R. Payri, T. Fansler, et al., IJER editorial: The future of the internal combustion engine, *Int. J. Engine Res.*, **21**, No. 1, 3–10 (2020).
2. A. K. Oppenheim, *Combustion in Piston Engines: Technology, Evolution, Diagnosis and Control*, Springer, UK (2013).
3. J. Xu, Flow analysis of engine intake manifold based on computational fluid dynamics, *J. Phys.: Conf. Series*, **916**, No. 1, Article ID 012043 (2017).
4. K. Gocmen and H. S. Soyhan, An intake manifold geometry for enhancement of pressure drop in a diesel engine, *Fuel*, **261**, Article ID 116193 (2020).
5. S. A. Sulaiman, S. H. M. Murad, I. Ibrahim, and Z. A. Abdul Karim, Study of flow in air-intake system for a single-cylinder Go-Kart engine, *Int. J. Automotive Mech. Eng.*, **1**, No. 1, 91–104 (2010).
6. M. A. Jemni, G. Kantchev, and M. S. Abid, Influence of intake manifold design on in-cylinder flow and engine performances in a bus diesel engine converted to LPG gas fuelled, using CFD analyses and experimental investigations, *Energy*, **36**, No. 5, 2701–2715 (2011).
7. K.-H. Kim and K.-J. Kong, 1D–3D coupling for gas flow analysis of the air-intake system in a compression ignition engine, *J. Marine Sci. Eng.*, **9**, No. 5, 553 (2021).
8. W. Pereira de Oliveira, S. de Morais Hanriot, and J. Mendes Queiroz, Analysis of pulsating phenomena in an ICE intake manifold using lumped parameter and transfer matrix methods, *Appl. Acoust.*, **178**, Article ID 108029 (2021).
9. H. Song and H. Cho, Flow characteristics and noise reduction effects of air cleaners of automobile intake systems with built-in resonators with space efficiency, *J. Eng. Res. (Kuwait)*, **9**, No. 3, 294–302 (2021).
10. G. R. D. Souza, C. D. C. Pellegrini, S. L. Ferreira, F. Soto Pau, and O. Armas, Study of intake manifolds of an internal combustion engine: A new geometry based on experimental results and numerical simulations, *Therm. Sci. Eng. Prog.*, **9**, 248–258 (2019).
11. R. C. Costa, S. D. M. Hanriot, and J. R. Sodré, Influence of intake pipe length and diameter on the performance of a spark ignition engine, *J. Braz. Soc. Mech. Sci. Eng.*, **36**, No. 1, 29–35 (2014).
12. Y. M. Brodov, B. P. Zhilkin, and L. V. Plotnikov, Influence of intake/exhaust channel lateral profiling on thermomechanics of pulsating flows, *Tech. Phys.*, **63**, No. 3, 319–324 (2018).
13. S. H. Abidi and M. M. Hasan, Variation of turbulent kinetic energy due to dimples in intake manifold for diesel engine, *Case Stud. Therm. Eng.*, **27**, Article ID 101299 (2021).
14. L. V. Plotnikov, B. P. Zhilkin, and Y. M. Brodov, Thermomechanical improvement of gas–air systems of turbocharged piston internal-combustion engines, *J. Eng. Phys. Thermophys.*, **93**, No. 6, 1557–1566 (2020).
15. U. Demir, G. Coskun, H. S. Soyhan, A. Turkcan, E. Alptekin., and M. Canakci, Effects of variable valve timing on the air flow parameters in an electromechanical valve mechanism — A CFD study, *Fuel*, **308**, Article ID 121956 (2022).
16. M. A. Iurk, S. H. Och, L. M. Moura, V. C. Mariani, and E. Domingues, Maximizing volumetric efficiency using stochastic optimization techniques for internal combustion engines, *Appl. Therm. Eng.*, **199**, Article ID 117603 (2021).
17. V. V. Naga Deepthi and K. Govindarajulu, Optimization of inlet and exhaust manifold on a single cylinder diesel engine to enhance the combustion, *Int. J. Innovative Technol. Exploring Eng.*, **8**, No. 10, 1408–1411 (2019).
18. F. Brusiani, S. Falfari, and G. Cazzoli, Tumble motion generation in small gasoline engines: A new methodological approach for the analysis of the influence of the intake duct geometrical parameters, *Energy Procedia*, **45**, 997–1006 (2014).
19. L. V. Plotnikov and B. P. Zhilkin, Influence of gas-dynamical nonstationarity on local heat transfer in the gas–air passages of piston internal-combustion engines, *J. Eng. Phys. Thermophys.*, **91**, No. 6, 1444–1451 (2018).
20. Y. A. Grishin, V. A. Zenkin, and R. N. Khmelev, Boundary conditions for numerical calculation of gas exchange in piston engines, *J. Eng. Phys. Thermophys.*, **90**, No. 4, 965–970 (2017).
21. G. A. Mukhachev and V. K. Shchukin, *Thermodynamics and Heat Transfer* [in Russian], Vysshaya Shkola, Moscow (1991).

22. S. S. Kutateladze and A. I. Leontiev, *Heat and Mass Transfer and Friction in a Turbulent Boundary Layer* [in Russian], Énergoatomizdat, Moscow (1985).
23. L. V. Plotnikov, *Nonstationary Thermal Mechanical Processes in Gas Exchange Systems of Turbocharged Piston Engines* [in Russian], Izd. Ural′sk. Univ., Ekaterinburg (2020).
24. L. V. Plotnikov, Thermal-mechanical characteristics of stationary and pulsating gas flows in a gas-dynamic system (In relation to the exhaust system of an engine), *Therm. Sci*., **26**, No. 1A, 363–374 (2022).
25. I. A. Davletshin, N. I. Mikheev, A. A. Paereliy, and I. M. Gazizov, Convective heat transfer in the channel entrance with a square leading edge under forced flow pulsations, *Int. J. Heat Mass Transf*., **129**, 74–85 (2019).