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PHYSICAL AND NUMERICAL MODELING OF THERMOMECHANICAL PROCESSES IN GAS–AIR SYSTEMS OF PISTON ENGINES UNDER GASDYNAMIC-NONSTATIONARITY CONDITIONS

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It is well known that as of today, internal combustion engines are the most widespread energy sources among heat engines. Therefore, one relevant problem in the development of world energy is to improve operating processes, and also to modernize systems and elements of piston internal combustion engines with the aim of improving their technical and economic indices. In the present paper, the authors have given new information on nonstationary gasdynamics and local heat transfer of pulsating flows in gas–air flow ducts of internal combustion engines, and also have proposed methods for improving the processes in intake and exhaust systems. Experimental investigations were conducted on full-scale models of a single-cylinder internal combustion engine with supercharging and without it. Physical features of pulsations of gas flows in the engines' gas–air flow ducts have been described. Calculated and experimental dependences of the change in the instantaneous velocity and the pressure of the gas flow in the gas–air flow ducts with time have been presented. Particular emphasis was placed on an analysis of the intensity of heat transfer in gas–air flow ducts of different configurations. It has been shown that lateral profiling of intake and exhaust pipelines exerts a positive influence on the technical and economic indices of piston engines without supercharging. A method to reduce pulsations of the pressure and velocity of gas flows (on the average, by a factor of 2) in the intake pipeline of a supercharged internal combustion engine has been proposed, which leads to an improvement of the reliability of the entire engine.

Keywords: *piston engine, gas–air systems, turbosupercharging, pulsating flows, nonstationary gasdynamics, local heat transfer, improvement of gas exchange.*

Introduction. The operating efficiency of internal combustion engines (ICEs) is largely dependent on the perfection of thermomechanical processes occurring in intake and exhaust systems [1–3]. The gasdynamic and heat-transfer characteristics of gas flow in gas–air flow ducts have been rather neglected until the present time. This is due to the fact that improving the heat transfer in the cylinder was initially more relevant and efficient from the viewpoint of raising the technical and economic indices of ICEs (this research area has been well thought-out and understood, in particular, we can note serious studies [4, 5]). At the moment, engine technology has reached a level where upgrading any characteristic of the engine even by several tens of a percent is a serious achievement for specialists. Therefore, at present, scientists and engineers look for novel areas of improving ICE operating processes. One of such areas, in the authors′ opinion, is studying and improving thermomechanical processes in intake and exhaust systems of engines under the conditions of gasdynamic nonstationarity (unsteadiness).

It is well known that the processes of intake of air and release of exhaust gases in engines are pulsating, high-frequency, and unsteady. The periods of gas transfer in modern ICEs are hundredths and even thousandths of a second. Gas flows in intake and exhaust pipelines change with a frequency up to 100 Hz or more. Therefore, because of the complexity of the object of investigation, an experimental approach to investigating thermomechanical processes was taken as a basis. Here, it is not quite correct to study gasdynamic and heat-transfer characteristics of the gas flow in intake and exhaust systems by numerical modeling only under stationary conditions and/or using quasi-stationary approaches, since it is common knowledge that the heat-transfer indices of gas flow under nonstationary conditions may differ from the stationary case 2 to 4 times. Here, we can single out works in which the gasdynamic nonstationarity is shown to exert no substantial influence on the intensity of heat transfer in hydraulic systems or to lead to a certain growth in [6–9]. At the same time, there are studies in

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which, conversely, it has been established that the nonstationarity causes the heat transfer intensity in hydraulic systems to considerably reduce [10–12]. It should be noted that in the field of engine technology, most of the investigations is conducted in stationary regimes of blowing of intake and exhaust systems. And just a few scientific works can be singled out where the processes of intake and exhaust in ICEs are investigated under nonstationary conditions [13–16].

In the present paper, we give results of mathematical modeling of the ICE operating processes and of experimental investigation into the nonstationary gasdynamics and local heat transfer of gas flows in gas–air flow ducts of different configurations as applied to piston engines with supercharging and without it.

Distinctive Features of Gasdynamic Nonstationarity in Gas–Air Flow Ducts of Piston Engines. In the authors′ opinion, it is expedient to consider in detail the distinctive features of pulsations of gas flows, since they determine in many respects the intensity of heat transfer in gas–air flow ducts of piston engines and accordingly the areas of thermomechanical improvement of the processes. First, the pulsations are characterized by the fact that air flow in the system fully stops for a fairly long time under the action of the camshaft (channel cross section is closed), and thereafter is restored again when the valve is opened after a break. During the ICE operating cycle, the time when the valve is open (the process of input or release of the gas is implemented) amounts to approximately 35–45% of the total duration of the cycle. The valve is in the closed position the rest of the time and accordingly no air enters the system.

Second, it should be emphasized that the physical mechanisms of flows in the process of air intake into the cylinder and the process of release of the gases from the cylinder are fundamentally different. A motive factor of air flow in the process of intake into the ICE without supercharging is rarefaction which is created in the cylinder by the piston moving from the top down, i.e., rarefaction waves are formed. In the process of release of the gases from the cylinder, the physical pattern is reverse: a source of motion of the flow is excess pressure in the cylinder, i.e., after opening the exhaust valve, compression waves appear.

Third, there are the distinctive features of formation of pulsations in piston ICEs equipped with a supercharging system. In the case in question, a source of air motion in the intake system is primarily the centrifugal compressor which pumps air into the cylinder under excess pressure (in contrast to ICEs without supercharging), i.e., in this case it is compression waves now (not rarefaction waves as in ICEs without supercharging) that appear in the process of intake. Here, the rarefaction waves in the subsonic region are known to be stable, and the compression waves, unstable [17].

In the authors′ opinion, these features of pulsating flows must be taken account of in investigating gasdynamics and heat transfer in intake and exhaust systems, since they determine in many respects the flow-rate characteristics and thermomechanics of the flows and accordingly possible areas of improvement of the processes of intake and release.

Experimental Setups and Instrumentation Base. To investigate the gasdynamics and local heat transfer of pulsating flows in intake and exhaust systems, we developed and fabricated experimental setups representing full-scale models of a single-cylinder engine of dimension 8.2/7.1 (cylinder diameter 82 mm, piston stroke 71 mm) with a turbosupercharging system and without it. The mechanism of gas distribution (drive of the intake and exhaust valves) of the ICE model was borrowed from the engine of a VAZ-OKA automobile. The gas-distribution phases (periods of opening and closing of the valves) and the valve lift of the experimental setups corresponded to those for the sited engine. The crankshaft was driven by an asynchronous motor whose rotational frequency was controlled by the frequency converter in the range from 500 to 3000 min^{-1}. Supercharging was implemented using a turbocompressor (turbosupercharger) of Russian manufacture with standard designation TKR-6. In the course of experiments, the rotational frequency of the turbocompressor rotor n_{tc} varied from 30,000 to 60,000 min^{-1}. A detailed description of the experimental setups has been presented in [8].

For the investigations, we created an automated experimental data acquisition and processing system on the basis of an analog-to-digital converter. Instantaneous values of the air-flow velocity w_x and of the local heat-transfer coefficient α_x were determined by a constant-temperature hot-wire anemometer [19]. Hot-wire anemometry for investigating the gasdynamics and local heat transfer of gas flows was selected from an analysis of the literature, in particular, [20, 21], and also from mature approaches to studying the motion of nonstationary flows. The applicability of hot-wire anemometry to investigating flows in the processes of intake and exhaust in piston engines has been shown in [22]. In our case a sensing element of the hot-wire-anemometer sensors in both cases was the Nichrome wire of diameter 5 μm and length 5 mm. To measure the air-flow velocity, use was made of the sensor with a free wire arranged perpendicularly to the axis of the gas–air flow duct, and to determine α_x, use was made of the sensor with a wire lying on the Teflon substrate which was mounted flush with the channel wall. Rotational frequencies of the crankshaft were measured by a tachometer. The procedure of determining the local heat-transfer coefficient and the assessment of the experimental error have been described in [16] in greater detail.

Figure 1 shows the test configuration of the working portion of the gas–air flow duct of the experimental setup and the sites of installation of the sensors of the hot-wire anemometer to measure instantaneous values of the gas-flow velocity

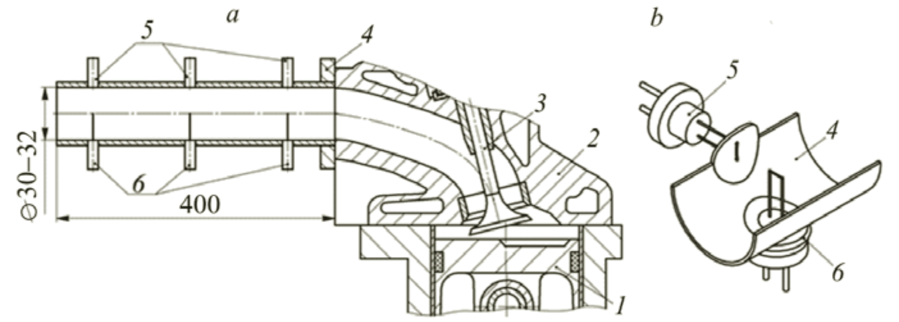

Fig. 1. Configuration of the gas-air flow duct of a piston ICE under study (a) and the layout of hot-wire-anemometer sensors in the pipeline (b): 1) piston; 2) integral cylinder head; 3) intake or exhaust valve; 4) pipeline under study; 5) hot-wire-anemometer sensor to determine the local heat-transfer coefficient; 6) hot-wire-anemometer sensor to determine the local gas-flow velocity. The dimensions are in mm.

and local heat transfer. In connection with the insufficient amount of experimental data on nonstationary gasdynamics and local heat transfer in ICE gas–air flow ducts, with account of the gasdynamic nonstationarity and the insufficient knowledge of this issue, it was methodologically expedient to select, as the initial base, a traditional straight pipeline with a circular cross section.

Verification of Experimental Data Obtained under Laboratory Conditions. Prior to investigating experimentally gasdynamics and local heat transfer in ICE gas–air flow ducts, we carried out numerical modeling using ACTUS (ABB Turbo Systems) and Dizel′-RK (N. É. Bauman Moscow State Technical University) software systems. A comparison of individual modeling results and experimental data is presented in Fig. 2.

It has been established that the most reliable results of numerical modeling of the process of intake and exhaust are in the period of open valves, whereas in the remaining interval of the operating cycle of the engine, these results should be considered as preliminary results to be verified experimentally.

Experimental data obtained on the single-cylinder laboratory setup were verified in the functional engine of the VAZ-OKA automobile. Figure 3 gives the superimposed plots of the change in the velocity of the air flow and the exhaust gases in the intake and exhaust pipelines with time for different rotational velocities of the crankshaft, which have been obtained on the laboratory model of the engine and the functional piston ICE. It can be seen from the figure that the data obtained on the laboratory setup are qualitatively confirmed on the functional engine, which holds true of the intake system and the exhaust system alike. For example, disagreements between the maximum values of the gas velocity do not exceed 10% (Fig. 3a). It should be noted that in both cases (laboratory setup and the functional ICE), in the intake system, we observe fluctuations of the air flow after closing the intake valve. Furthermore, the process of intake begins not with the zero values of the flow velocity, which is characteristic of all the operating regimes of the ICE model and the functional engine. It should be emphasized that analogous results were also obtained for the process of release of exhaust gases (Fig. 3b). In this case there are somewhat greater disagreements between the quantitative indices (within 15–18%), which is attributed to different physical properties of the working medium: air with a temperature of about 22$^{\text{o}}$C was used in investigations on the laboratory benches, and the exhaust gases with a temperature of about 300$^{\text{o}}$C, in the functional ICE.

On the basis of the conducted experiment investigations, we have proposed a corrective procedure of matching the quantitative indices (in particular, flow-rate characteristics) of the laboratory investigation data and the data obtained on the functional ICE. This procedure can be scaled to fit other thermomechanical processes in the gas–air flow ducts of piston engines.

Lateral Profiling of the Channels in the Gas–Air Flow Ducts of Piston Engines. Traditionally, to ensure a uniform velocity field in the gas–air flow ducts of engines, use is usually made of channels with a circular cross-sectional shape. At the same time, in not fully symmetric channels, stable longitudinal vortex flows develop [23–25] which may have an effect on gas dynamics and heat transfer in the gas–air flow ducts of piston engines. Thus, it was hypothesized that one method to improve thermomechanical processes in intake and exhaust systems is lateral profiling of the channels.

In the present investigation, use was made of portions with a cross section in the shape of a square and an equilateral triangle. The portion with a nonsymmetric cross section amounted to approximately 30% of the total length of the gas–air

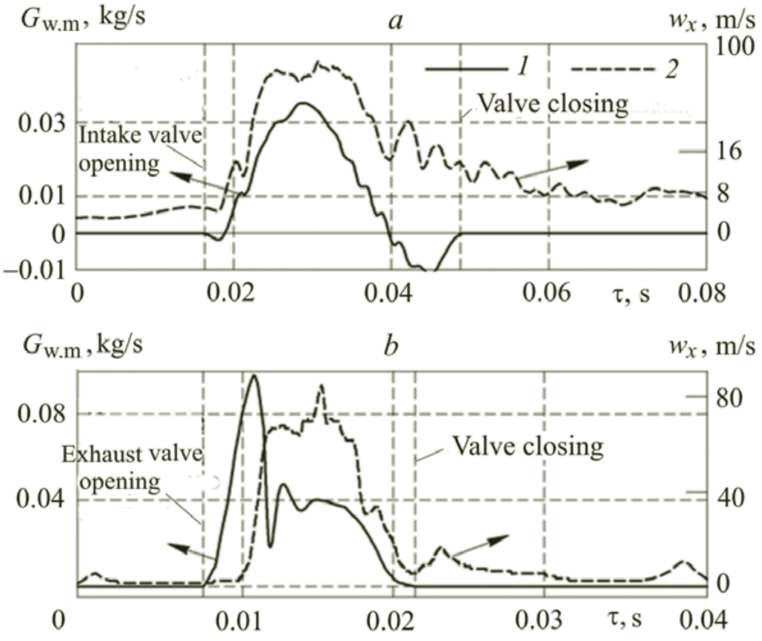

Fig. 2. Comparison of the calculated (1) and experimental (2) dependences of the mass flow rate $G_{\text{w.m}}$ and the local velocity w_x of the gas in the engine′s gas–air flow ducts on the time τ at different rotational frequencies: a) in the intake pipeline of the ICE without supercharging at $n = 1500$ min^{-1} and b) in the exhaust pipeline of a turbosupercharged ICE at $n = 3000$ min^{-1} and $n_{\text{TC}} \approx 100{,}000$ min^{-1}.

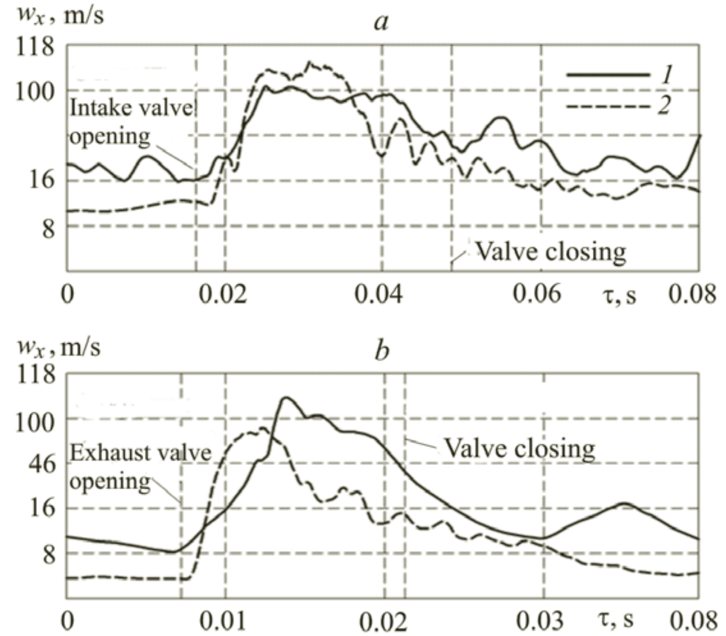

Fig. 3. Local ($l_x = 110$ mm and $d = 32$ mm) velocities of air w_x in the intake pipeline at $n = 1500$ min^{-1} (a) and of exhaust gases in the exhaust pipeline at $n = 3000$ min^{-1} (b) vs. time τ: 1) functional engine; 2) laboratory ICE model.

flow ducts. For the intake pipeline, the equivalent (hydraulic) diameter d_e was equal to 32 mm, and for the exhaust one, to 30 mm. Steps on the transition region of portions of different shapes were smoothed out by plastic material. The interior surface of the gas–air flow ducts had a technically smooth surface with an average roughness size of 6.3 μm.

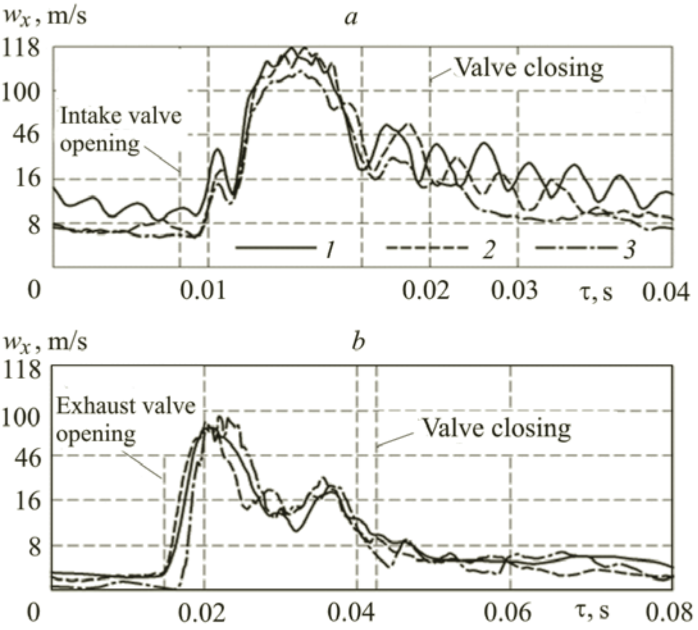

Fig. 4. Local (l_x = 110 mm and d = 32 mm) velocities of air w_x in intake at n = 3000 min^{-1} (a) and exhaust pipelines at n = 1500 min^{-1} (b) vs. time τ and varying cross section: 1) circle, 2) square, and 3) triangle.

Figure 4a shows that after the intake valve is closed (the process of intake is completed), strong vibrational phenomena are observed. Here, the faster suppression of the vibrational phenomena in the case where the profiled portions are used in the gas–air flow ducts is, in the authors′ opinion, due to the stabilizing influence of longitudinal vortex structures formed in the corners of triangular and square profiles. It can be seen that this effect (vibrational phenomena after closing the valve) is absent, in practice, from the exhaust system (Fig. 4b), which, as the authors believe, is associated with different mechanisms of formation of pulsating flows.

Lateral profiling of the gas–air flow ducts also exerts an influence on the flow-rate characteristics of intake and exhaust systems (Fig. 5). It has been shown (Fig. 5a) that a number of advantages over the traditional tube of circular cross section can be gained due to the placement of profiled portions in the intake pipeline. For example, an increase, on the average, of 22% has been established in the volumetric rate of flow of the fresh charge entering the cylinder, and also a growth in the slope of the curve of the air flow rate as a function of the rotational frequency of the crankshaft in the operating range n when the "triangular" portion is used. Installing the portion with a square cross section leads to a growth in the rate of flow of the air through the intake system in the range 5–15% compared to the traditional structure.

The processing of experimental data for the exhaust pipeline with a square cross section under the conditions of constant exhaust pressure has shown that in this case the volumetric flow rate grows linearly, in fact, with the crankshaft rotational frequency (Fig. 5b). Here, the volumetric rate of flow of the air through the "square" exhaust pipeline is greater, on the average, by 8–20% than that through the cylindrical pipeline. The "triangular" portion used in the exhaust system leads to a substantial growth in the volumetric flow rate, which is the most pronounced at low frequencies of the crankshaft. In the authors′ opinion, the recorded effect is caused by the above-mentioned stabilizing influence of stable vortex structures formed in the corners of the square channel.

From the data resulting from the mathematical modeling (ACTUS, Dizel′-RK) and the analytical calculations (Professor B. A. Sharoglazov′s methodology) [26] of the operating process of full-scale engines, it may be stated that integrated modernization of the intake and exhaust systems by lateral profiling leads to an improvement of the basic indices of a piston ICE (depending on its operating regime):

to an increase of 4.0–24.2% in the coefficient of admission;
to a reduction of 9.7–24.1% in the residual-gas coefficient;
to an increase of 3.5–17.0% in effective power;
to a change of ±1.0–2.5% in the specific flow rate of the fuel.

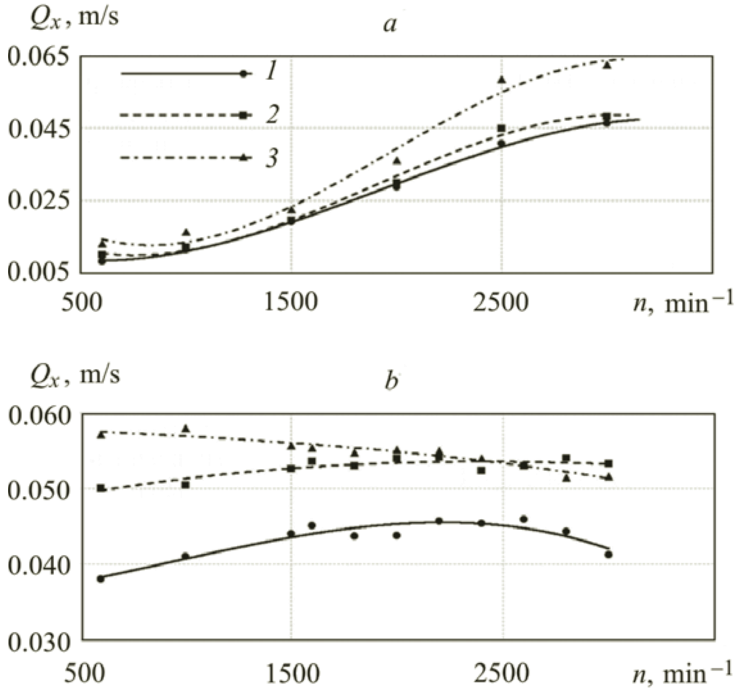

Fig. 5. Local volumetric rates of air flow Q_x through intake (a) and exhaust pipelines (b) vs. rotational frequency of the crankshaft n and varying cross section: 1) circle, 2) square, and 3) triangle.

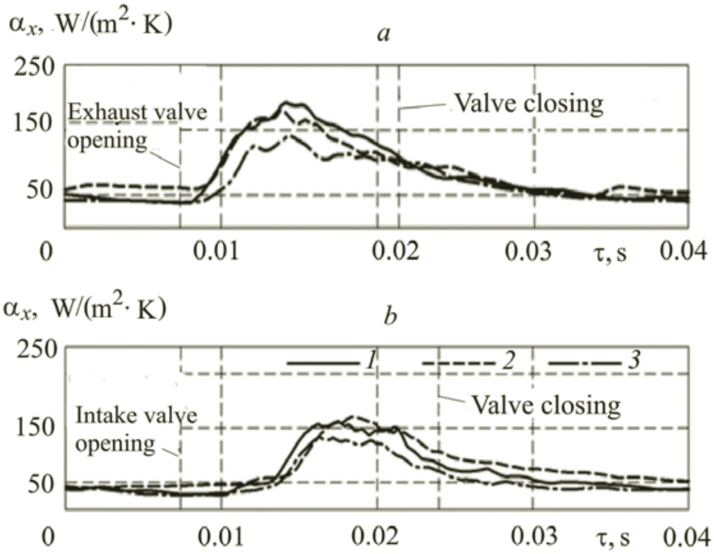

Fig. 6. Instantaneous local heat-transfer coefficients α_x in gas–air flow ducts of varying cross section vs. angle of rotation of the crankshaft φ at the crankshaft′s rotational frequency $n = 3000\ \text{min}^{-1}$ in the intake pipeline ($l_x = 110$ mm and $d = 32$ mm) (a) and in the exhaust pipeline ($l_x = 140$ mm and $d = 32$ mm) (b) at different cross-sectional shapes: 1) circle, 2) square, and 3) triangle.

The substantial change in the gasdynamic conditions of the gas–air flow ducts of the engines when profiled portions are used in them also leads to a transformation of the dependences of the local heat-transfer coefficient with time τ as shown in Fig. 6. It can be seen from Fig. 6a that we have the greatest reduction (on the average, of 12%) in heat-transfer intensity when

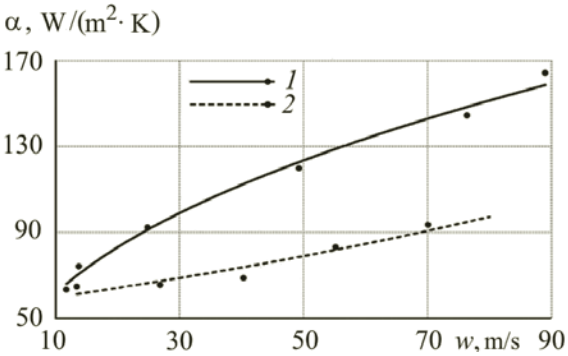

Fig. 7. Heat-transfer coefficients α vs. average velocity of the air flow *w* in the piston-engine′s exhaust pipeline in different regimes of flow of the gas: 1) stationary flow and b) pulsating flow.

the portion with a triangular cross-sectional shape is used in the intake pipeline. Analogous results were also obtained by the authors for the exhaust pipeline (Fig. 6b): with the portion with a triangular cross-sectional shape, the heat-transfer intensity is reduced to 30%. More detailed data on the influence of lateral profiling of the channels on the intensity of heat transfer in the gas–air flow ducts of engines may be found in [27].

We can assess the influence of gasdynamic nonstationarity on the heat-transfer characteristics of the flow in the gas–air flow ducts of the engines, turning our attention to Fig. 7. A comparison of the values of the local heat-transfer coefficient α_x in static and pulsating regimes of motion of the flow shows that for the ICE intake pipeline, the gasdynamic nonstationarity leads to a substantial reduction in the heat transfer, which may amount to as much as 35%. Analogous data were also obtained for the process of exhaust [16].

Influence of Turbosupercharging on the Thermomechanics of Pulsating Flows in Gas–Air Flow Ducts of Piston Engines. In the literature sources devoted to the theory of operating processes and to designing piston engines, the installation of a turbocompressor (turbosupercharger) (TC) for supercharging of the ICE is considered exclusively as an efficient method to enhance the mass rate of flow through the cylinders of the engine and accordingly to improve its technical and economic indices [28, 29]. It should be noted that in actual fact, the issue of the influence of a TC on the thermomechanical characteristics of pulsating flows in gas–air flow ducts is not touched upon. Hydrodynamically, it is usually agreed that the TC is a static element of the gas–air system, which creates hydraulic resistance and simultaneously is a means for heating up the engine. At the same time, from the literature sources and pilot experiments, it may be assumed that the installation of a TC will exert a substantial influence on the gasdynamics and heat transfer of pulsating flows in the intake and exhaust systems of a piston ICE [30, 31], since its blading has a mechanical effect on the flow, creating external turbulence in relation to the head mainstream.

Figure 8 gives the plots of the local velocity of the air flow in the intake pipeline of a piston ICE with turbosupercharging and without it versus time. It is shown that there are significant differences in the regularities of change in the local velocity of the air flow in engines with turbosupercharging and without it. Thus, the maximum values of the flow velocity in the intake system of the ICE with a TC are 25% higher than in the engine without supercharging. Here, the vibrational phenomena of the air flow after closing the intake valve in the turbosupercharged engine are more pronounced. Opposite effects were established for the exhaust system with supercharging: the TC used leads to a reduction in the maximum values of the gas flow and to a smoothing of vibrations throughout the engine′s operating cycle.

The differences found in the gasdynamic characteristics of pulsating flows in the intake and exhaust pipelines must exert an influence on the intensity of heat transfer in gas–air flow ducts of piston ICEs with turbosupercharging and without it. It has been established that with a TC, the intensity of heat transfer in the exhaust pipeline is reduced at all the excess pressures and the rotational frequencies of the engine′s crankshaft (Fig. 9). Here, the decrease in the maximum values of the local heat-transfer coefficient at the excess pressure $p_{\text{out}} = 1.0$ bar in the exhaust system with a TC amounts to 10–15%, whereas at $p_{\text{out}} = 0.5$ bar, the reduction amounts to 15–20% now.

The reduction in the intensity of heat transfer to the walls of the exhaust pipeline in the presence of the TC must have a positive effect on the engine′s operating process and technical and economic indices, since in this case the greater heat drop will usefully be expended in the TC, rather than will "go" to the channel walls. In the exhaust pipeline of the ICE with a TC,

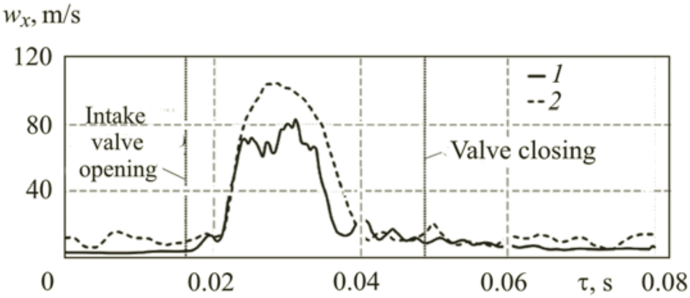

Fig. 8. Local (l_x = 110 mm and d = 32 mm) velocities of air w_x in intake pipeline of a piston ICE without supercharging (1) at n = 1500 min^{-1} and with supercharging (2) at n = 1500 min^{-1} and n_{TC} = 46,000 min^{-1} vs. time τ.

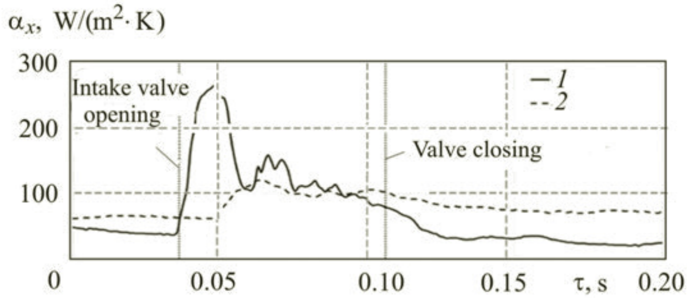

Fig. 9. Local (l_x = 140 mm and d = 32 mm) heat-transfer coefficients α_x in the exhaust pipeline vs. angle of rotation of the crankshaft φ in a piston ICE without supercharging (1) at n = 600 min^{-1} and the excess exhaust pressure p_{out} = 1.0 bar and with supercharging (2) at n = 600 min^{-1} and n_{TC} = 35,000 min^{-1}.

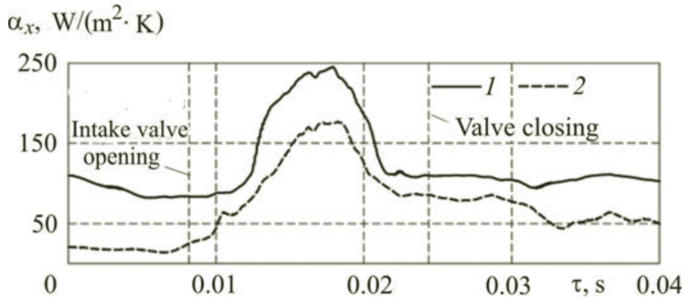

Fig. 10. Local (l_x = 150 mm and d = 32 mm) heat-transfer coefficients α_x vs. angle of rotation of the crankshaft φ in the intake pipeline of a piston ICE with supercharging (n_{TC} = 35,000 min^{-1}) at the rotational frequency of the crankshaft n = 3000 min^{-1} at different configurations of the system: 1) without and 2) with release of air (G^* = 0.12).

in contrast to the engine without supercharging, the maximum values of α_x and its mean values alike grow at all the rotational frequencies of the crankshaft and the rotor of the TC.

Stabilization of Gas Flows in the Intake System of a Turbosupercharged Piston Engine. An analysis of the literature and of the results of conducted investigations has allowed the conclusion that in the intake system of a turbosupercharged ICE, substantial pulsations of velocity, pressure, and the local heat-transfer coefficient are observed which are attributable to the excess output of the TC in relation to the engine on certain regimes.

Stabilization of the air flow (reduction in velocity and pressure pulsations) was attained by the release of a certain fraction of the supercharge air from the intake pipeline, which can also lead to a reduction in the intensity of local heat transfer [32]. It has been established that when a certain part of the air compressed in the supercharger is released from the intake pipeline, we have a reduction in the flow velocity and pressure pulsations, and also a decrease in the local heat-transfer coefficient with preservation of the characteristics of the rate of flow through the engine (Fig. 10).

The obtained effects will make it possible to decrease differences in the operation of the cylinders of multicylinder ICEs, to reduce the noise level, to increase the service life of the engine, and also to raise the compressor efficiency. To attain the maximum effect of suppression of the pulsations, we drew process flow diagrams enabling us to determine the optimum fraction of release G^* as a function of n and n_{TC}. An engineering study was made of installing such a system on a 8DM-21LM diesel produced by the OOO "Ural Diesel Engine Plant" [33].

CONCLUSIONS

According to the conducted set of investigations, we can draw the following basic conclusions:

1. Methods of numerical modeling in studying the processes in gas–air flow ducts of piston ICEs (with turbosupercharging and without it) may be employed as estimating ones to predict basic technical and economic indices and individual characteristics of gas flows and must be supplemented (confirmed) with the results of experimental research and development works.
2. In the work, an area of modifying gas–air flow ducts has been updated which leads to an increase in the rate of flow of the air (up to 2%) entering the cylinder and to an improvement of removal of exhaust gases from it (reduction of 15–20% in the residual-gas coefficient) due to the lateral profiling of the intake and exhaust pipelines of piston ICEs.
3. It has been established that the implementation of turbosupercharging leads to significant differences in the regularities of change in the gasdynamic and heat-transfer characteristics of gas flows in ICE gas–air flow ducts. On this basis, it has been shown that for the engines with a TC, it is necessary to seek fundamentally different research and technology solutions to improve intake and exhaust processes.
4. A method for reducing pressure and velocity pulsations of the gas flow (on the average, by a factor of 2) in the intake pipeline of turbosupercharged ICEs, and also a method for reducing the local heat-transfer coefficient (on the average, by 25%) have been proposed, which will enable us to diminish differences in the operation of the cylinders of a multicylinder engine, to reduce the noise level, and to increase the service life.
5. The obtained results can be used in both developing novel designs of intake and exhaust systems of piston ICEs and modernizing engines that are already in operation. Moreover, the thermophysical regularities found in the engines′ gas–air flow ducts can be used to refine mathematical models, the so-called digital twins of piston ICEs.

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NOTATION

d, inside diameter of the pipeline, mm; $G_{\text{w.m}}$, mass flow rate of the air, kg/h; G^*, relative fraction of release (disposal) of the supercharge air; l_x, governing linear dimension, mm (it is reckoned from the flow inlet into the pipeline); n, rotational frequencies of the crankshaft of a piston ICE, min^{-1}; n_{TC}, rotational frequency (speed) of the TC rotor; min^{-1}; p_{out}, excess exhaust pressure, MPa; Q_x, local volumetric rate of flow of the air, m^3/s; w_x, local velocity of the gas flow, m/s; α_x, local heat-transfer coefficient, W/(m^2·K); α, averaged heat-transfer coefficient, W/(m^2·K); τ, time, s. Subscripts: w.m, working medium; TC, turbocompressor.

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