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The gas-dynamic unsteadiness effects on heat transfer in the intake and exhaust systems of piston internal combustion engines

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ABSTRACT

This article presents the results of experimental research into the gas-dynamic and heat-exchange parameters of gas flows in the intake and exhaust pipelines of piston ICEs (internal combustion engine) taking into account the nonstationary nature of the gas exchange processes. Some characteristic times of transient processes (recovery time and relaxation time) are established during the gas flow recovery in round pipelines. Based on the obtained data, the degree of non-stationarity or unsteadiness of the gas-dynamic processes in piston ICE pipelines can be established. It is demonstrated that there are two types of resolution for gas-dynamic unsteadiness. It is established that unsteadiness reduces the instantaneous local heat transfer intensity in the pipelines of piston ICEs by 1.3–2.5 times. A method is proposed for taking the thermomechanical unsteadiness into account in thermal calculations by applying the heat transfer mobility correction coefficient for classical equations that are used to calculate the local heat transfer coefficient.

1. Introduction

There are many different power machines and plants in which the operating process occurs in pulsating modes (the gas flows in their elements in a context of gas-dynamic unsteadiness). They include piston internal combustion engines (ICE), compressors, bladed machines and many others. At the same time, the gas-dynamic unsteadiness significantly influences the transport process mechanisms in their gas-air paths. It is known that the deeper the unsteadiness, the more significant the non-equilibrium and, consequently, its effect on the transport mechanism [1]. Hence, there are two inter-related tasks. First, it is necessary to have remarkably clear indicators (criteria) that allow us to unambiguously determine the degree of unsteadiness of gas flows in the power machine paths in order to evaluate their actual technical and economic performance, calculate the gas exchange processes and effectively control them. Secondly, it is necessary to have an idea of the physical mechanisms of the effect of the gas-dynamic unsteadiness on the processes in gas-air paths of power machines in order to improve their processes and effectively influence them. To date, these problems have been poorly covered in the published literature. Therefore, it is quite relevant to obtain initial information on the levels of unsteadiness of processes in the pulsating gas flows, develop criteria that determines the degree of the gas-dynamic unsteadiness, update the physical transport mechanisms in gas-air paths and develop a methodology for taking into account the effect of the gas-dynamic unsteadiness of flows in pipelines of different configurations on local heat transfer.

To a significant extent, the efficiency of piston internal combustion engines depends on the perfection of the processes taking place in their gas-air paths (in the intake and exhaust pipelines). The gas exchange processes (the air intake and exhaust gas release) in piston engines are high-frequency and non-steady. The gas exchange periods in modern piston engines account for hundredths of a second. The gas flow parameters in the intake and exhaust pipelines change periodically with frequencies of up to 100 Hz and higher. The flow accelerations and decelerations reach values of up to 150,000 m/s^2. At the same time, it is known that the gas flow heat exchange rate under non-stationary conditions can be reduced by 2–4 times as compared with the steady-state case. For example, Valueva, proceeding from numerical modelling of gas dynamics [2] and heat exchange [3] of pulsating gas flows in pipelines of different configurations, has established a significant decrease in the heat transfer rate compared to a steady flow that can reach 2.5 times. Simakov [4] and Holley and Faghri [5] have

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Nomenclature

w	flow velocity, m/s
j	flow acceleration, m/s^2
p	static pressure, MPa
d	pipeline diameter, mm
n	engine crankshaft speed, rpm
K_{mh}	heat transfer mobility factor
l	linear dimension, mm (measured from the gas flow pipeline inlet)

Greek symbols

α	heat-transfer factor, W/(m^2·K)
τ	time, s

Subscripts

x	local parameter
$\bar{}$	averaged parameter value
e	equivalent (hydraulic) diameter
bb	initial exhaust overpressure
res	recovery time
rel	relaxation time
st	steady flow
unst	unsteady flow
1	the parameter related to the sensor near the channel wall
2	the parameter related to the sensor in the centre of the channel

Abbreviations

ICE	internal combustion engine

also shown in their experimental works a significant reduction in heat transfer under the non-stationary conditions with respect to different thermal engineering problems. Detailed research into the physical mechanism for reducing the heat transfer rate of pulsating flows in pipelines are devoted to a number of works by Kraev [6,7]. He explains the decrease in the heat transfer intensity by three separate effects: the effect on the convective heat exchange of transient heat conduction; the dynamic rearrangement of the gas flow structure in the boundary layer at a constant flow rate; and flow changes. At the same time, Kraev emphasises that the mechanism of the effect of acceleration and deceleration of the flow on turbulence has not yet been fully explained [7]. Moreover, some works provide other results that indicate that the gas-dynamic unsteadiness does not significantly affect the heat transfer rate in pipes or leads to its growth by 30–40% in comparison with the steady flow. For example, the numerical simulation by Wang and Zhang [8] established that the local heat transfer factor increases by an average of 30% with a pulsating gas flow. Similar data were obtained by Russian researchers Mikheev et al. [9] based on experimental research. Similar results can also be found in the well-known publications of Park et al. [10] and Chung et al. [11], in which it was shown that the gas-dynamic unsteadiness does not essentially affect the local heat transfer intensity. It should be noted that the data described above were obtained in a laboratory environment without reference to specific technical or technological machinery, or, more precisely, without reference to the type of unsteadiness typical of the processes in a particular machine.

It should be noted that insufficient focus has been on the study of gas dynamics and heat transfer of gas flow in the intake and exhaust systems of internal combustion engines (ICE). This is because the improvement of heat transfer in the cylinder was initially more relevant and effective from the point of view of improving the technical and economic performance of piston engines. At the moment, engine manufacturing has reached such a level that an increase in any engine index by at least a few tenths of a percent is a serious achievement for professionals. Therefore, at present, researchers and engineers are looking for new possibilities of improving the ICE processes. One of such possibilities, according to the authors, is the study and improvement of processes in the intake and exhaust pipelines of engines in the gas-dynamic unsteadiness context. As noted above, the gas exchange processes in the engines are pulsating and unsteady, therefore it is not entirely correct to study the gas-dynamic and heat-exchange characteristics of the gas flow in gas-air paths only in the steady-state conditions and/or using quasi-stationary approaches by numerical simulation. The information on the gas exchange processes in piston ICEs under unsteady conditions are very limited and very contradictory.

The classic experiments by Ricardo [12] and Zass [13] performed in the early 20th century can be referred to as the first research into the air flow in the cylinder of a piston engine. They studied the twist of the flow in a cylinder using a vane anemometer depending on the engine crankshaft speed. Later, some research into gas dynamics and heat exchange of flows in steady-state gas flow conditions was initiated and followed by the development of mathematical models for one-dimensional gas exchange process modelling [14]. Since the development of computer and measuring equipment, the thermal anemometry method has become widely used in the study of unsteady-state and turbulent flows including in gas-air paths of piston internal combustion engines [15]. The development of software packages for the mathematical modelling of gas dynamics and heat transfer has led to a large number of gas exchange process studies with their help [16]. Unfortunately, only some works verify results obtained on the basis of numerical modelling based on experimental studies [17].

This paper considers the characteristics of gas-dynamic unsteadiness in relation to thermal-mechanical processes in the intake and exhaust systems of piston internal combustion engines. The study is aimed at clarifying the physical mechanism of pulsating currents and establishing the regularities in the variation of the gas-dynamic and thermal characteristics of the flows in the intake and exhaust channels in the gas-dynamic unsteady conditions for improving the gas exchange quality in piston ICEs.

The key objectives of the research are as follows:

- to identify the physical features of the gas dynamic conditions of heat transfer of the high-frequency and pulsing flow in the gas-air tracts of piston engines;
- to establish the degree of the gas-dynamic unsteadiness of gas flows in the intake and exhaust pipelines of piston engines;
- to develop a methodology for taking into account the effect of the gas-dynamic unsteadiness of flows in pipelines of different configurations on the local heat transfer.

By solving the problems, it will be possible to expand the knowledge base on thermophysical processes in the course of gas flows under unsteady-state conditions, provide the basis for the development of engineering methods for calculating the intake and exhaust systems of engines, and also allow the development of perspective piston engine designs with heat recovery of exhaust gases.