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EXPERIMENTAL STUDIES OF THERMOACOUSTIC MODULE OF AUTOMOBILE ENGINE

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ABSTRACT

This article presents the results of experimental studies of thermoacoustic module of vehicle engine obtained at various engine loads and speeds. The thermoacoustic module is intended for noise reduction during release of exhaust gases due to thermoacoustic effect upon cooling of the gases. Recovery of thermal energy of exhaust gases is used to decrease engine warming-up time after cold start and to increase fuel efficiency at this operation mode. The results of the experimental studies of thermoacoustic module are presented by a set of parameters including noise reduction of exhaust gases in comparison with basic exhaust system, aerodynamic resistance of heat exchanger of thermoacoustic module on the exhaust side, hydraulic resistance of heat exchanger tube space on coolant side, and other parameters.

Key words: internal combustion engine, exhaust gases, thermoacoustic module, experimental studies, exhaust noise, temperature, pressure.

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1. INTRODUCTION

One of the major issues of modern megalopolises is acoustic contamination of ambient environment resulted from numerous vehicles. Necessity to reduce noise is stipulated by many factors including negative impact on human health. Contribution of vehicles into total acoustic contaminations of modern urban environment reaches 60% [1].

Nowadays innovative approaches are developed aimed at noise reduction of exhaust gases (EG), designing and experimental verification of the developed appliances are carried out. One of promising approaches to noise reduction is based on thermoacoustic effect. This effect provides decrease in sound pressure of acoustic waves upon decrease in EG temperature. Its practical embodiment is provided by thermoacoustic module of automobile engine (TAMAE) containing EG coolant and mounted in exhaust system in addition to basic silencer.

Experimentally established is that application of TAMAE reduces noise by about 2 dB upon EG cooling by 100°C [2]. It should be mentioned that efficient TAMAE would permit to satisfy the requirements of advanced regulations on EG noise reduction to 71 dBA and even lower [3].

Thermal power transferred to coolant upon EG cooling is dissipated by cooling system of internal combustion engine (ICE), it also can be used for acceleration of engine warming-up and reduction of fuel consumption.

ICE cold start-up is known to be a major problem since engine mechanic efficiency upon cold start-up is significantly lower in comparison with conditions when the engine components are heated to operation temperature [4].

Thus, ICE cold start-up at 0°C increases fuel consumption by 13.5% [5], and at the temperature of engine oil of about 20°C friction losses in the engine are by 2.5 times higher than those for preheated engine oil [6].

It should be mentioned that decrease in warming-up time reduces harmful emissions with exhaust gases immediately after engine cold start [7]. In addition, there is an interrelation between harmful substances in EG upon cold start and season. According to this interrelation EG toxicity at this mode is lower in summer time [8]. Decrease in content of harmful substances in EG upon cold start is especially important in the context of law enforcement aimed at minimization of ICE negative effect on environment.

2. METHODS

TAMAE testing procedures are based on studies of main operation parameters of the module mounted in standard ICE exhaust system.

Experimental studies of TAMAE performed on engine dynamometric test rig provide high reliability of measured data which is, with some assumptions, restricted only by accuracy of instrumentation.

The module is experimentally studied by instrumentation comprised of EG pressure and temperature sensors mounted at the module inlet and outlet, coolant pressure and temperature sensors mounted at inlet and outlet of the module cooling circuit, coolant flow meter, signal converter, and recording devices. The applied procedure provides analysis of the acquired data. EG flow rate is determined by calculations based on readings of ICE control unit.

During the TAMAE testing the influence of load/speed modes of ICE operation on the main performances of the module is determined including reduction of EG noises in comparison with basic exhaust system, aerodynamic resistance of heat exchanger tube space, hydraulic resistance of the tube space, and other parameters.

In addition, decrease in time required for achieving engine operation temperature and decrease in fuel consumption at engine warming-up are determined enabled by TAMAE. The obtained experimental data made it possible to predict thermal power removed by TAMAE from engine EG and thermal power transferred to TAMAE by coolant.

The module was tested upon the following conditions:

- ICE load: from 10 to 100%;
- ICE crankshaft RPM: from 850 to 4,600 min^{-1};
- inlet coolant temperature: more than 80°C;
- coolant flow rate: from 0.5 to 1 kg/s.

Figure 1 illustrates TAMAE 3D layout depicting engineering and assembling variants [9].

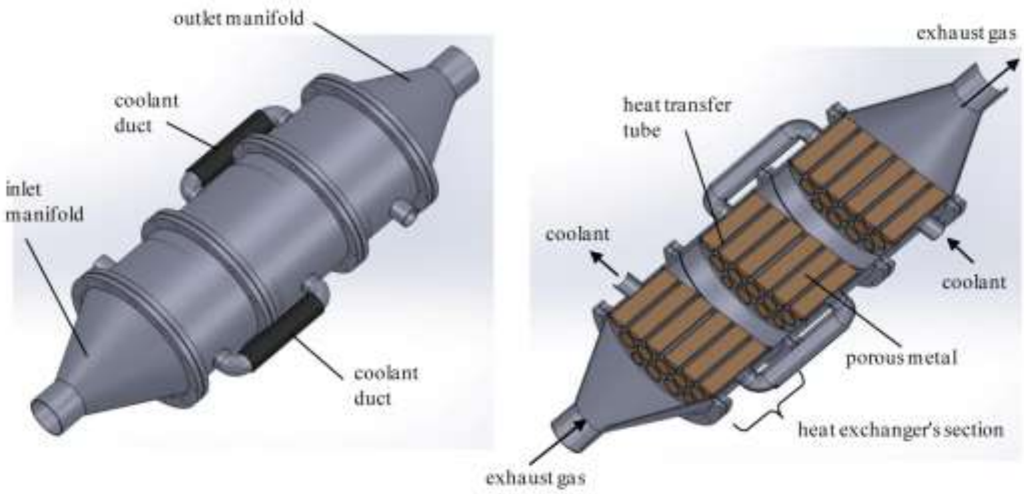

Figure 1. TAMAE 3D layout

TAMAE is detachable, it is comprised of bodyworks and three-section shell-and-tube heat exchanger with serial arrangement of the sections, it is used for EG cooling. Selection of shell-and-tube heat exchanger is stipulated by wide range of configuration of such appliances which are successfully applied in chemical, power engineering and processing industries [10]. EG flow moves in tubes and coolant circulates in tube space.

TAMAE is characterized by the following performances: dimensions –900×312×420 mm, nominal coolant flow rate – 1 kg/s, heat exchange surface area on coolant side –0.517 m^2, heat exchange surface area on EG side, depending on volume of applied porous metal (PM) – 1.49-1.66 m^2.

Figure 2 illustrates schematic layout of heat exchange tube depicting directions of coolant motion. Prediction of heat exchange processes in heat exchanger of TAMAE between coolant and EG separated by cylindrical walls of heat exchange tubes is discussed in details in [11].

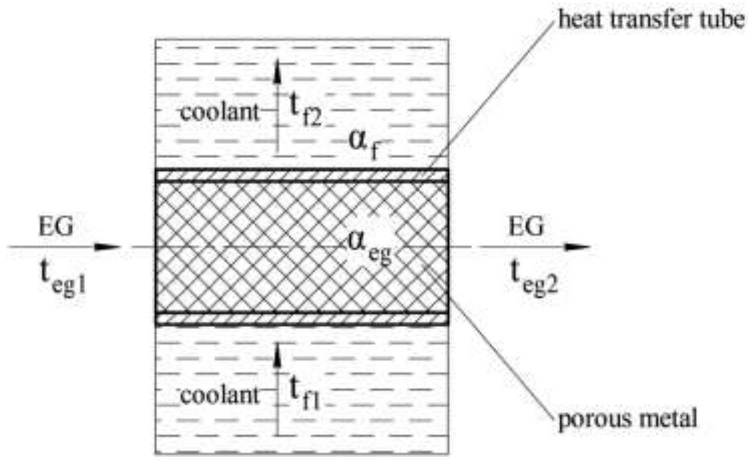

Figure 2. Schematic view of heat exchange tube

In order to intensify heat exchange in EG cooler and to increase heat exchange surface area in the restricted space, it was decided to apply heat exchange elements fabricated of PM mounted inside the heat exchange tubes. Possibilities of such solution are confirmed by projects devoted to study of heat exchange between coolant flow and PM [12, 13].

3. RESULTS

In this section we present the results of TAMAE tests obtained during ICE operation at various load/speed modes. The obtained experimental data are preliminary, since these tests were carried out with the first TAMAE embodiment.

The main experimental results and analysis of the obtained data are given below.

1) EG noise reduction in comparison with basic exhaust systems.

EG noise reduction provided by TAMAE was compared with performances of vehicle basic exhaust system. Figure 3 illustrates the plot based on the obtained data of ICE operation modes and coolant flow rate of 0.5 kg/s.

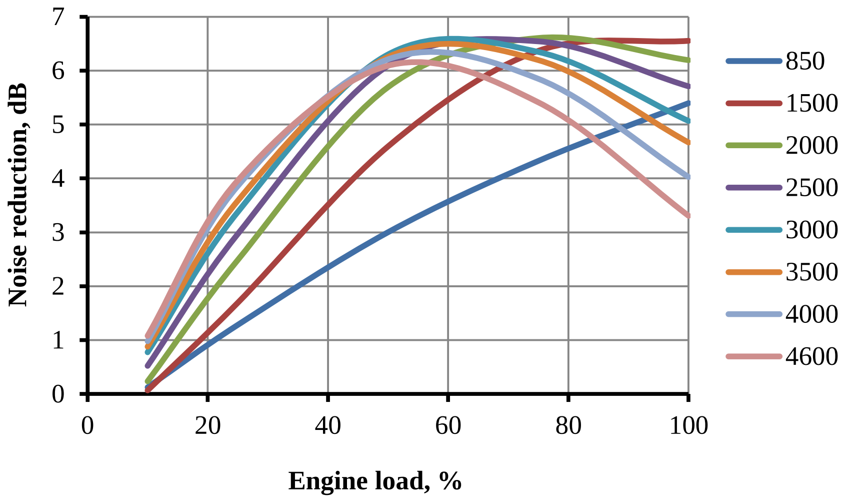

Figure 3. EG noise reduction as a function of ICE operation modes

The obtained results demonstrate low efficiency of prototype with regard to EG noise reduction in overall range of ICE RPM and load from 10 to 15% when noise reduction does not exceed 2 dB. However, capabilities of standard exhaust system more than enough satisfy regulations for noise at these modes, so that operation of TAMAE at this mode is of low priority.

The highest TAMAE efficiency is achieved upon ICE operation at the RPM from 3000 to 4600 min^{-1} and average loads which is related with high efficiency of heat exchanger in this range. Such performance of TAMAE compensates disadvantages of conventional reactive silencer applied in vehicle exhaust systems. Sufficient TAMAE efficiency should be mentioned in overall range of ICE RPM and load from 20 to 40%.

2) Aerodynamic resistance of TAMAE on EG side

Aerodynamic resistance of heat exchanger tube side was determined by the difference of recordings of EG pressure sensors mounted at prototype inlet and outlet. Figure 4 illustrates aerodynamic resistance of prototype as a function of load/speed modes of ICE operation.

The obtained aerodynamic resistance in excess of 8,000 Pa should be considered high. It requires for certain measures aimed at restrictions of aerodynamic resistance in preset range.

One of approaches is decrease in the number of heat exchange elements fabricated of PM when internal space of several heat exchange tube is not filled with elements.

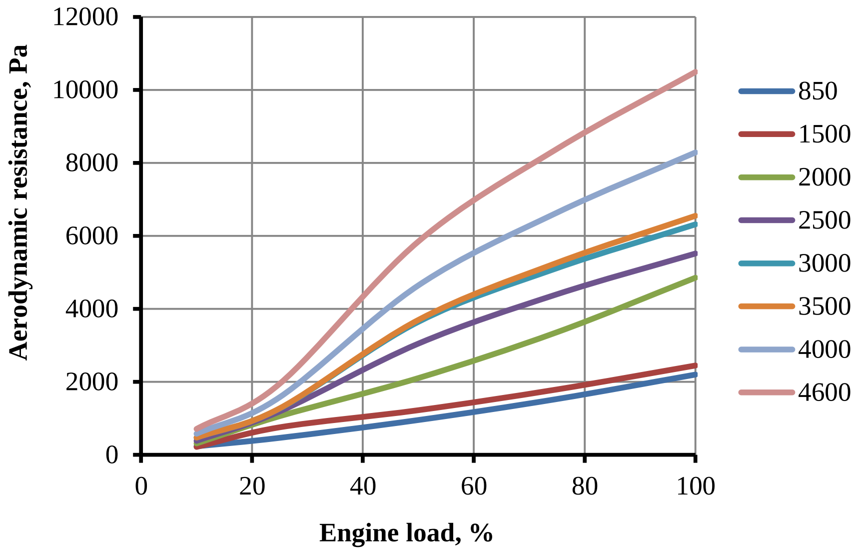

Figure 4. Aerodynamic resistance as a function of ICE loads and speeds

Herewith, it would be required to determine distribution of hollow heat exchange tubes in tube sheet and in heat exchange sections. For instance, location of hollow heat exchange tubes in the center of heat exchange tube sheet is not reasonable due to increased nonuniformity of flow distribution across heat exchange tubes, since EG flow moves along TAMAE central axis, and hollow tubes are characterized by lower aerodynamic resistance.

3) Hydraulic resistance of prototype on coolant side

Hydraulic resistance was determined by the difference between readings of coolant pressure sensors installed on inlet and outlet from TAMAE cooling circuit. Figure 5 illustrates hydraulic resistance of the module as a function of coolant flow rate plotted upon variation of ICE crankshaft RPM from 850 to 4,600 min^{-1}.

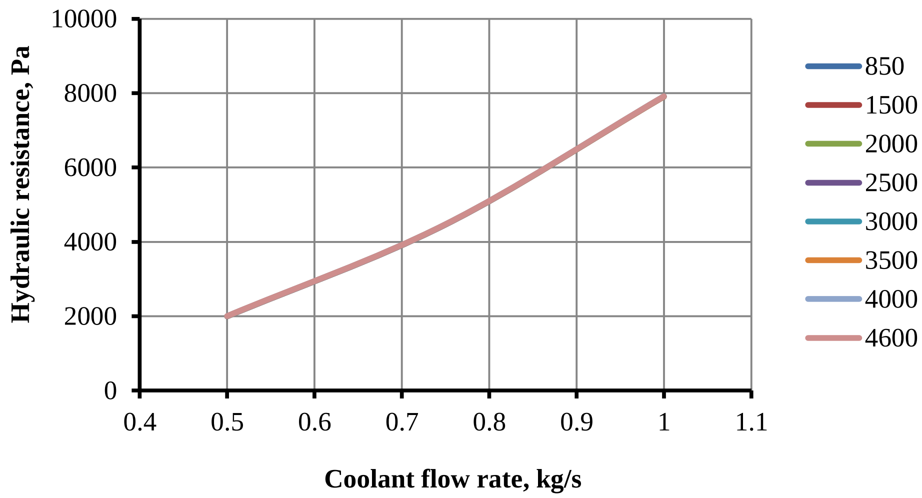

Figure 5. Hydraulic resistance as a function of coolant flow rate.

The obtained results demonstrate that the hydraulic resistance of prototype does not exceed 8,000 Pa and is satisfactory.

It is also established that the variation of coolant temperature does not exert significant influence on hydraulic resistance since the coolant density varies insignificantly in the existing range of coolant temperature.

4) Thermal power N_{EG} transferred to TAMAE from engine EG and thermal power N_C transferred to TAMAE from coolant.

The thermal power from hot EG is transferred to coolant in two stages. At first the thermal power N_{EG} is transferred to heat exchange tubes and then the thermal power N_C is transferred from the coolant tubes. The difference between N_{EG} and N_C makes it possible to estimate the heat exchange efficiency in TAMAE.

N_{EG} and N_C are determined with consideration for bulk flow and specific heat capacity and their temperature drop between TAMAE inlet and outlet.

The obtained results demonstrate that the difference between N_{EG} and N_C can be up to 10%, which is related with heat losses appearing during heat exchange.

5) Effective ICE performances improved by the use of TAMAE.

Effective performances are presented by the time of engine warming up Δt and decrease in fuel consumption at engine warming-up time ΔGt. During the experiments the coolant flow rate via TAMAE heat exchanger was 0.5 kg/s and the coolant temperature, when ICE was considered to be warmed, was set to 60°C.

Δt and ΔGt were determined in two stages: without and with TAMAE. In the first variant Δt and ΔGt equaled to 319 s and 1.17 kg/h, and in the second variant - to 275 s and 1.1 kg/h, respectively. Therefore, the use of TAMAE in exhaust system made it possible to reduce the warming-up time Δt by 13.8%. The use of TAMAE reduced fuel consumption during engine warming-up ΔGt by 6.4%.

4. DISCUSSION

This article describes briefly testing procedure of TAMAE installed in standard exhaust system of vehicle together with description of TAMAE design which explains location and interaction of main module elements.

The experimental results of TAMAE are practically useful and can be applied for activities related with optimization of its design in the form of new designing and assembling solutions as well as applied materials and development of TAMAE operation algorithms.

The obtained values confirm reasonability of TAMAE application under conditions prevailing during urban driving. This would allow to reduce acoustic contamination of urban environment by vehicles with piston ICE.

Necessity to reduce aerodynamic resistance of TAMAE on EG side is established. Importance of this measure is stipulated by combined usage of TAMAE and other elements of exhaust system. As a consequence, cumulative backpressure of the system should not exceed maximum allowable values for standard exhaust system.

It should be mentioned that the obtained reduction ΔGt during ICE warming up results in increase of total engine efficiency which increases proportionally upon increase in number of cold starts.

Decrease in ICE warm up time reduces duration of engine operation with enriched fuel-air mixture. Since this mixture is characterized by incomplete combustion, then the reduced time of operation of catalyst converter with exhaust gases generated during combustion of this mixture can increase its lifetime.

5. CONCLUSIONS

Experimental studies of TAMAE provided detailed data array which could be used for fine tuning of calculated mathematical model applied for initial development of TAMAE and empirical dependences for prediction of physical processes in such devices, for instance, calculation of heat exchange processes in PM.

Experimental studies of TAMAE allowed to determine the influence of load/speed modes of ICE operation on the main performances of the module, including EG noise reduction in comparison with basic exhaust system, aerodynamic resistance of heat exchanger tube space, hydraulic resistance of heat exchanger tube space, as well as on ICE effective performances improved upon application of TAMAE.

In this work the effective performances are presented by ICE warm-up period and decrease in fuel consumption during engine warming-up.

The obtained experimental data made it possible to evaluate heat exchange efficiency by comparison of two thermal capacities obtained upon EG cooling and coolant heating in the module heat exchanger.

Pattern of noise reduction upon EG release at various ICE operation modes is analyzed, recommendations are given aimed at decrease in aerodynamic resistance of heat exchanger tube space.

The obtained experimental results of TAMAE can be used as preliminary initial data or reference materials for various R&D projects related with development of components for transport or other applications. Moreover, on the basis of the obtained data it is possible to carry out economic feasibility study of TAMAE in exhaust system.

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