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Preparation and Analysis of Experimental Findings on the Thermal and Mechanical Characteristics of Pulsating Gas Flows in the Intake System of a Piston Engine for Modelling and Machine Learning

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Abstract: Today, reciprocating internal combustion engines are used in many branches of the economy (power engineering, machine engineering, transportation, and others). In order for piston engines to meet stringent environmental and economic regulations, it is necessary to develop complex and accurate control systems for the physical processes in engine elements based on digital twins, machine learning, and artificial intelligence algorithms. This article is aimed at preparing and analysing experimental data on the gas dynamics and heat transfer of pulsating air flows in a piston engine's intake system for modelling and machine learning. The key studies were carried out on a full-scale model of a single-cylinder piston engine under dynamic conditions. Some experimental findings on the gas-dynamic and heat-exchange characteristics of the flows were obtained with the thermal anemometry method and a corresponding measuring system. The effects of the inlet channel diameter on the air flow, the intensity of turbulence, and the heat transfer coefficient of pulsating air flows in a piston engine's inlet system are shown. A mathematical description of the dependences of the turbulence intensity, heat transfer coefficient, and Nusselt number on operation factors (crankshaft speed, air flow velocity, Reynolds number) and the inlet channel's geometric dimensions are proposed. Based on the mathematical modelling of the thermodynamic cycle, the operational and environmental performance of a piston engine with intake systems containing channels with different diameters were assessed. The presented data could be useful for refining engineering calculations and mathematical models, as well as for developing digital twins and engine control systems.

Keywords: reciprocating engine; intake process; channel diameter; unsteady aerodynamics; gas flow; heat transfer; mathematical analysis; reciprocating engine performance

MSC: 41A30; 41A45

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1. Introduction

Improving the operational and environmental performance of reciprocating internal combustion engines (RICE) remains relevant for the development of many industries (power engineering, machine engineering, transportation, and others) [1]. Given the stringent requirements for environmental friendliness and RICE efficiency, there is a need to use ever more complex physical process control systems in engine systems based on machine learning and artificial intelligence algorithms [2]. Filling the cylinder with a working fluid (induction stroke) and cleaning the cylinder from exhaust gases (exhaust stroke) largely determine the technical, economic, and environmental performance of RICE [3,4]. Consequently, in order to develop efficient and accurate control systems for gas exchange processes, reliable experimental data on gas dynamics and the heat transfer of pulsating gas flows in intake and exhaust manifolds with different geometric dimensions are needed. The problem in obtaining these data lies in the complexity of the research target:

- the gas exchange system of a piston engine has a complex geometry with bends, obstacles, and moving elements (poppet valve);
- the gas flow in the system moves in a pulsating mode with a frequency of 10 to 100 Hz;
- the mechanics of gas flow in the system implies the presence of stagnant and vortex zones, as well as return and secondary flows.

Let us consider contemporary research by other authors relating to the gas dynamics and heat transfer of flows in RICE gas exchange systems. There are several research areas in the field:

(1) detailing data on physical processes in gas exchange systems;
(2) improving the design of parts and assemblies for RICE induction and exhaust systems;
(3) developing engine control systems, taking into account information about gas exchange processes based on mathematical models, machine learning, and artificial intelligence algorithms.

Within the framework of the first research area, there are a large number of multifaceted works. For example, Pranoto S. et al., studied in detail the effects of an obstruction (throttle valve) in the intake manifold on gas dynamics and air flows in a gasoline engine with the CFD method [5]. The authors focused on the position of the throttle valve in the manifold, the occurrence of large-scale vortices, and the scale of flow turbulence. Zhang S. et al., studied the effect of exhaust gas recirculation on the gas dynamics of the flow in the intake duct and engine cylinder with a numerical simulation [6]. The authors established patterns between the rate of exhaust gas recirculation, the rate of combustion of the fuel-air mixture, and the amount of NOx emissions. Furthermore, the importance of taking into account the gas-dynamic behaviour of the flow in the intake system for the processes of mixture generation and the combustion of fuel in the engine cylinder is shown in [7]. Yuan C. et al., studied ways of shaping gas exchange processes in linear motors [8]. It was established that the quality of gas exchange depends on the piston motion law. There are separate studies focusing on the effect of gas-dynamic unsteadiness on the intake and exhaust processes [9,10]. It is necessary to take into account the non-stationarity of the processes in the gas exchange system for a more accurate prediction of engine performance and more efficient operation of the turbocharging system. In particular, Yin S. et al., managed to increase the surge margin for a turbocharger by 14.5% by optimising the gas dynamics in the compressor and turbine [9]. In addition, a change in the gas-dynamic behaviour of the flows in the turbocharging system allows for power to be increased, while also improving the engine's efficiency and power response [11].

Some research has focused on the impact of the initial pressure in the intake pipeline on the gas dynamics of flows and engine performance [12–16]. Liu Z. et al., found that an aircraft engine at an altitude of 2000 m had increased heat losses, which caused a 2% reduction in efficiency [12]. Similar data were obtained in [13]. Ma F. et al., determined the optimal valve timing settings for various physical parameters at the inlet and outlet [14]. Mazuro P. and Kozak D. focused on the in-cylinder parameters of RICE aviation and the reliability of its parts and assemblies [15]. Researchers and specialists have also paid a great deal of attention to the features of the intake process at low (negative) temperatures [17,18]. The importance of these studies is due to the change in air density, the appearance of icing on the internal surfaces of pipelines, and the deterioration of conditions for the combustion of the fuel-air mixture.

There are also a large number of various design solutions within the framework of the second research area (relating to the improvement of gas exchange systems for piston engines) [19–24]. So, Wang T. et al., developed a special controlled valve for the intake system, with which it was possible to change the gas-dynamic behaviour of the flows in the engine cylinder [19]. This contributed to the creation of vortex structures, changing the intensity of turbulence and the flow structure in the cylinder to improve mixture formation and combustion. Shah S.S. et al., finetuned the geometric dimensions (diameter and length) of a gasoline engine in order to obtain maximum power [20]. Similar issues were addressed in [21]. It was established that the optimisation of the intake system's configuration leads to an increase in torque of up to 41% and a simultaneous decrease in specific fuel consumption within 8% for a crankshaft speed of 1200 rpm. Gangaraju et al., dealt with strength issues in relation to the intake manifolds of uprated engines [22].

Some works have shown the significant effect of valve timing (periods of the opening and closing of the intake and exhaust valves) on the gas dynamics of flows and RICE performance [25–27]. In particular, Perceau M. et al., found that the optimisation of valve timing can increase a piston engine's efficiency by up to 1% [25]. Similar results are described in the article [26]. Jung J. et al., studied the impact of valve timing on RICE environmental performance [27].

In recent years, the development of high-precision engine control systems has been promoted, taking into account the peculiarities of the flow of gas exchange processes based on mathematical models, machine learning, and artificial intelligence methods. Machine learning algorithms are intensively used in various fields of science and technology to create optimisers, develop control systems for technical equipment, and address related issues [28–30]. Song Y. et al., created a mathematical description of a multicriteria optimisation of the gas dynamics of flows and the geometry of intake and exhaust channels in an engine head pack through machine learning methods, in which the design constraints and boundary conditions of variable flow parameters in the gas exchange system and the RICE cylinder were refined [28]. Moreover, researchers and specialists are increasingly turning to artificial neural networks to reduce the amount of harmful substances in engine exhaust gases [31,32], to optimise fuel injection into the cylinder for RICE operating modes [33], and to solve other technical problems. Such process optimisation helps reduce NOx emissions by up to 30% and increase the efficiency of a piston engine by up to 2% [32]. However, in most cases, machine learning methods and neural network-based optimisers require a large amount of reliable experimental data about the described processes.

To meet the strict requirements relating to harmful substance emissions in exhaust gases, up-to-date engines are equipped with electronic control units that monitor the status of the main systems and, in particular, the physical parameters of gas exchange processes in real time [34–36]. For the efficient operation of such control systems, it is necessary to develop accurate one-dimensional mathematical models based on a large amount of verified experimental data in a wide range of engine operating modes. Therefore, it is a critical task for the development of reciprocating engines to obtain, analyse, and mathematically describe experimental data on the thermal and mechanical characteristics of pulsating gas flows in an intake system.

Thus, the key objectives of this study are:

- to obtain experimental data on the instantaneous values of the local air flow velocity and the local heat transfer coefficient in a gas-dynamic system with channels of various diameters, the configuration and boundary conditions of which are typical of a piston engine's intake system;
- to determine the flow characteristics of an intake system with channels of different diameters;
- to mathematically describe the pattern of changes in the intensity of turbulence of pulsating air flows in an intake system with channels of different diameters;
- to mathematically describe the pattern of change in the local heat transfer coefficient in an intake system with channels of different diameters;
- to evaluate the operational and environmental performance of a piston engine's intake system with channels of different diameters based on physical and mathematical modelling.

2. Research Test Bench and Measuring Equipment

Due to the complexity of the research target, an experimental approach was chosen to obtain data on the gas dynamics and heat transfer of pulsating flows in an intake system with channels of different diameters. A laboratory test bench was developed as a full-scale mock-up of a single-cylinder internal combustion engine (Figure 1).

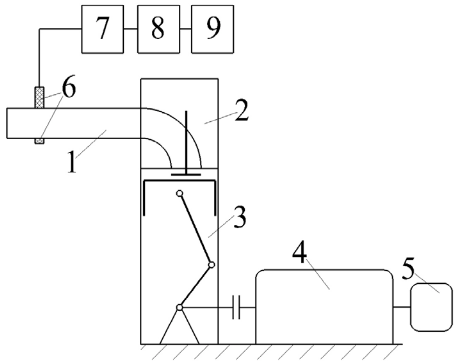

Figure 1. Diagram of the test bench and measuring equipment: 1—inlet channel; 2—cylinder head; 3—cylinder-piston group of the engine; 4—electric engine; 5—frequency converter; 6—hot-wire anemometer sensors (channels w_x and α_x); 7—hot-wire anemometer; 8—analogue-to-digital converter; 9—personal computer.

The piston engine model had all the main parts and assemblies typical of RICE (crank mechanism, cylinder-piston group, block head, gas distribution mechanism, intake and exhaust systems). The model prototype is an automobile engine from the VAZ company (Tolyatti, Russia). The key geometric dimensions are: cylinder diameter—82 mm; piston stroke—71 mm; inlet channel inner diameter—32 mm; exhaust channel diameter—30 mm; valve lift—9 mm; and total length of the intake system—400 mm. Given in Figure 2 is the studied section of the intake system with an indication of the main elements, geometric dimensions, and measuring sensors.

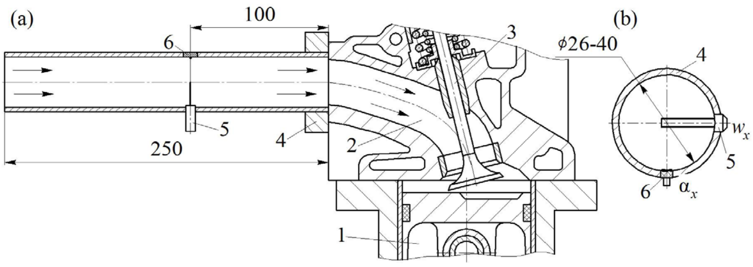

Figure 2. Diagram of the intake system (**a**) and cross section of the control section (**b**) (arrows indicate the air flow direction): 1—piston; 2—supply channel; 3—head of the engine pack; 4—inlet pipe; 5—speed sensor; 6—thermal sensor.

A peculiarity of the piston engine model's operation was that it did not have a fuel system. Therefore, the fuel in the cylinder was not burned. The engine model's crankshaft drive was driven with an electric motor and a control system based on a Schneider Electric frequency converter. The crankshaft speed varied in the range from 600 rpm to 2800 rpm. The set speed was maintained with an accuracy of ±1.0% of the current value. The valve timing (opening and closing times of the intake and exhaust valves) corresponded to that of the prototype engine and remained unchanged during the experiments (Figure 3). Accordingly, the source of pulsating air movement in the intake system was the vacuum in the cylinder created by the piston moving from top dead centre to bottom dead centre.

The working medium in the experiments was air with a temperature t = 21 ± 1 °C and barometric pressure p_o = 98 ± 0.3 kPa.

In these experimental studies, inlet pipes with different diameters d were used (Figure 4). The base value of the intake pipe's inner diameter was 32 mm. Additionally, pipes with diameters d = 26 mm and d = 40 mm were made with 3D printing. The pipes' inner surface had an average roughness of 6.3 μm (technically smooth surface). The inlet pipes had technical holes for measuring sensors at distances of 100 mm and 200 mm from the window in the head of the engine pack. However, the main findings in the article are given for one control section at a distance l_x = 100 mm in order to ensure that the material is presented compactly.

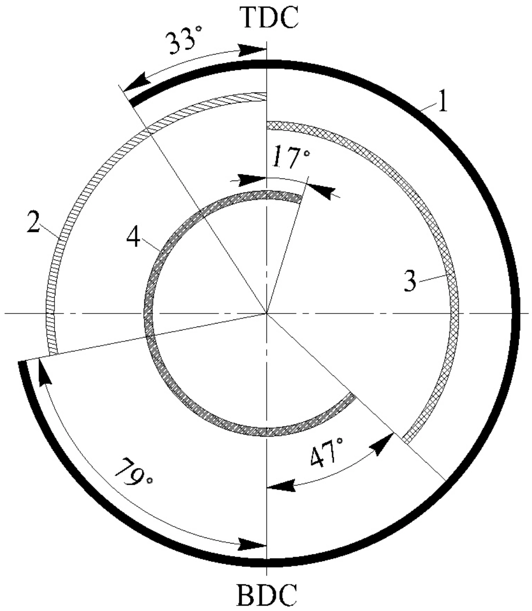

Figure 3. Valve timing for this study: 1—intake process; 2—compression process; 3—expansion process; 4—exhaust process; TDC—top dead centre; BDC—bottom dead centre.

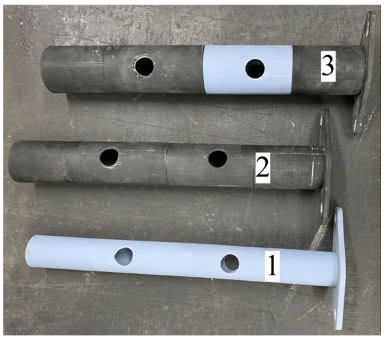

Figure 4. Photographs of the examined inlet pipes with different inner diameters *d*: 1—*d* = 26 mm; 2—*d* = 32 mm (basic configuration); 3—*d* = 40 mm.

The thermal anemometry method was used to obtain data on the local air flow velocity w_x and the local heat transfer coefficient α_x. The measuring system was built on the basis of a constant temperature hot-wire anemometer (Dantec Dynamics) and thermal sensors. To determine w_x and α_x, various types of sensors were used depending on the sensitive element's location (Figure 2). In our case, the sensitive element of the heat loss anemometer sensors was a nickel-chromium filament with a diameter of 5 µm and a length of 5 mm. To measure the air flow velocity, a sensor with a free thread placed perpendicular to the axis of the pipeline was used. To determine α_x, a sensor mounted flush was used with the wall of the pipeline and with a thread lying on a fluoroplastic substrate. The local heat-transfer factor was determined with the indirect calibration method according to S.S. Kutateladze, which is based on the basic indicator of the local heat transfer rate of a well-studied reference process, for which a permanent-set heat transfer in a long rectilinear tube of circular cross-section was chosen for the case (l/d = 50). In working conditions, the thread had a temperature of about 120 °C. The data from the constant temperature hot-wire anemometer were fed into an analogue-to-digital converter (ADC) from National Instruments, after which they were transferred to a computer for further processing in dedicated software. The response rates of the ADC, thermal sensor, and hot-wire anemometer were chosen, taking into account the intake process time (taking into account the frequency of air flow pulsations in the intake system).

The relative uncertainty of measuring the local air flow rate was ±2.55%, and the local heat transfer coefficient was ±5.72%. The description of the instrumentation base and the methodology for determining w_x and α_x are presented in more detail in the author's articles [4,37].

Tests on a gasoline engine were used to verify laboratory data and simulation results. A photograph of the engine with an indication of the main elements is shown in Figure 5. The main engine parameters for bench tests were:

- engine type—gasoline, spark ignition;
- number and arrangement of cylinders—in-line, two-cylinder;
- turbocharging system—absent;
- rated power—21.5 kW at n = 5600 rpm;
- maximum torque—36.5 Nm at n = 4000 rpm;
- piston diameter—82 mm;
- piston stroke—71 mm;
- compression ratio—9.9;
- valve lift height—9.0 mm;
- inlet pipe diameter (basic)—32 mm;
- outlet pipe diameter—30 mm;
- length of the intake system—450 mm.

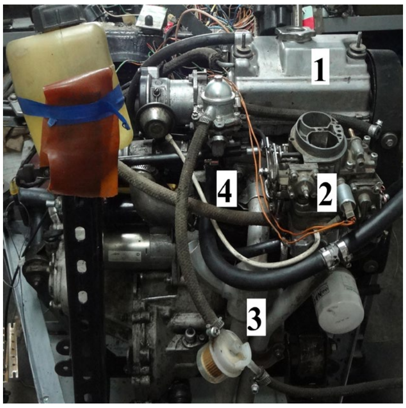

Figure 5. Gasoline engine for verification of laboratory research data and modelling results: 1—engine block head; 2—inlet pipeline; 3—exhaust manifold; 4—cylinder block.

Bench tests of the engine were carried out without load for crankshaft speeds from 1000 rpm to 3000 rpm. Measuring instruments were similar as in laboratory studies (as for the engine model). The inner diameter of the inlet pipeline was 32 mm. The hot-wire anemometer sensor for determining the flow velocity was also located at a distance of 100 mm from the engine block head.

In this article, the effects of the intake pipe's diameter on a piston engine's operational and environmental performances were additionally assessed based on the physical and mathematical modelling of the RICE cycle of operations in the Diesel-RK programme (Russia). This is necessary to demonstrate the importance of obtaining reliable experimental data for verifying mathematical models and setting up engine control systems based on artificial intelligence algorithms.

In the Diesel-RK programme, the gas parameters in the engine cylinder and gas exchange system channels are determined by a step-by-step solution of various equations for the conservation of energy, mass, and the equation of state, which are recorded for open thermodynamic systems. The calculation of the parameters in the collectors and channels during gas exchange in the Diesel-RK program was carried out using quasi-static methods of gas dynamics. The dependence of the working medium's properties on chemical composition and temperature is taken into account in the calculation of gas exchange processes. It should be noted that the mathematical model of gas exchange takes into account the unsteady gas flow in the channels. The assumption of "complete mixing" and the instantaneous propagation of disturbances was used when calculating the quality indicators of gas exchange in engine cylinders. The entire volume of the cylinder was a single open thermodynamic system in which the gas parameters were determined. A multizone model is used to calculate the combustion process in gasoline engines. The Vibe method is used to calculate the heat release rate in a cylinder. The concentrations of harmful substances in the exhaust gases were calculated according to thermodynamic and empirical equations laid down in the Diesel-RK. NOx emissions are calculated by the thermal mechanism based on the Zel'dovich scheme. The zone model is used to determine temperatures (Professor V.A. Zvonov's method). The zone model for calculating the temperature divides the volume of the combustion chamber into zones. The temperature is different (temperature gradients differ significantly during the combustion process) in these zones. Accordingly, hot gases rise and cold gases remain at the bottom. Both hot and cold zones are considered uniform in temperature, but the air temperature depends on time in each of the zones. The volume of the zones and their positions change during combustion. Heat transfer in engine parts and assemblies is calculated separately for different surfaces, the temperatures of which are determined by solving the heat conduction problem. The coefficient of heat transfer from gases to the cylinder wall is determined by the Woschni formula. Somewhat more detailed information about the mathematical model for calculating a reciprocating engine's thermodynamic cycle can be found in [38,39].

3. Experimental Findings and Their Analysis

Changes in the speed of the pulsating flow over time for intake systems with channels with different diameters and at different crankshaft speeds were obtained in this study (Figure 6).

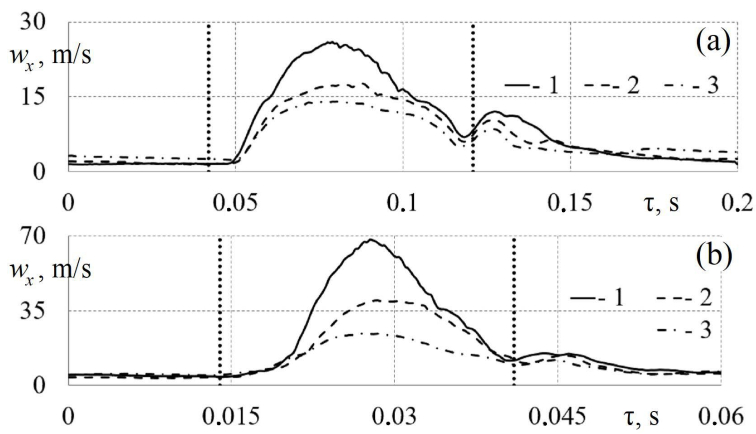

Figure 6. Dependences of the local (l_x = 100 mm) air flow velocity w_x in the intake system of a piston engine on time τ for crankshaft speeds of 600 rpm (**a**) and 1800 rpm (**b**) for different intake channel diameters: 1—d = 26 mm; 2—d = 32 mm; 3—d = 40 mm. The vertical lines indicate the opening and closing times of the intake valve.

Figure 6 shows that an increase in the intake channel's diameter leads to a drop in the maximum speed in the intake system (this is typical for all the crankshaft speeds under research). There is also a second speed surge after the main peak with the intake valve closed. At the same time, the second peak has a noticeably lower amplitude while using a channel with a diameter of 40 mm. This indicates a smoothing of speed pulsations in the intake system due to an increase in its volume. The smoothing of speed pulsations in the intake system indirectly indicates a decrease in the system's hydraulic resistance and should potentially have a positive effect on engine performance in the form of an increase in specific power.

The presented data sets can be useful for verifying mathematical models, machine learning, and tuning control systems based on neural networks and artificial intelligence algorithms.

A comparison of data from laboratory studies on the model and tests on a gasoline engine is shown in Figure 7.

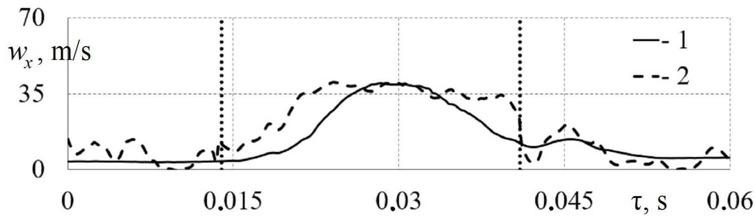

Figure 7. Dependences of the local (l_x = 100 mm) air flow velocity w_x in the intake systems of the engine laboratory model (1) and gasoline RICE (2) on time τ for a crankshaft speed of 1800 rpm and for d = 32 mm. The vertical lines indicate the opening and closing times of the intake valve.

Figure 7 shows that there is an acceptable visual coincidence of the functions $w_x = f\ (\tau)$ for laboratory studies and bench tests. Mathematical calculations showed that the standard deviation of laboratory research data on an engine model from the results of bench tests on a gasoline engine is no more than 10.8%. Therefore, it can be stated that the results of laboratory studies are reliable and can be used to accumulate data for modelling and machine learning.

An additional analysis of the functions $w_x = f\ (\tau)$ made it possible to determine that for the studied configurations of the intake systems, the Strouhal number Sh ranged from 0.2 to 0.25, while the magnitude of the relative pulsations varied from 2.5 to 3.0. Consequently, the flow pattern for pulsating air flows in the studied piston engine's intake system is classified as medium frequency [40]. This indicates that the gas-dynamic unsteadiness has a significant effect on the flow structure and the boundary layer. Therefore, one can expect significant changes in the heat exchange characteristics of pulsating flows in an intake system with channels with different diameters.

Primary experimental data on local heat transfer in the form of functions $\alpha_x = f\ (\tau)$ are presented in Figure 8 for intake systems with channels of different diameters and for different crankshaft speeds. An increase in the diameter of the inlet channel causes a decrease in the maximum values of the local heat transfer coefficient by 5–20%, compared to the basic configuration, which is typical of all crankshaft speeds studied. Conversely, a decrease in the channel diameter leads to a significant increase in the maximum values of α_x by 10–30% in comparison with the RICE intake system's basic geometry. At low frequencies of the crankshaft, fluctuations in the local heat transfer coefficient are observed in the function $\alpha_x = f\ (\tau)$. These fluctuations are substantially smoothed out with increased crankshaft speed.

The intensity of heat transfer in the intake system has effects on the amount of heating of the working medium during the intake process, the level of thermal stresses in the parts, and, as a result, the specific engine power. Accordingly, the correct consideration of the thermal and mechanical characteristics of pulsating flows in the intake system will improve the accuracy of mathematical models and engineering calculations, as well as create new approaches to engine control algorithms based on machine learning and artificial intelligence.

Turbulence intensity Tu was used to evaluate the pulsation component of the air flow in the intake system. Tu was determined as the ratio of the root-mean-square fluctuating velocity component to the average velocity of the flow under study. At the same time, for a pulsating air flow, the average speed with phase averaging for a complete engine cycle was found (at least five cycles were used for averaging). As a result, a function of the average air flow velocity in time for a pulsating air flow in the intake system was obtained, relative to which the pulsating velocity component was determined. The method for determining Tu is described in more detail in [41].

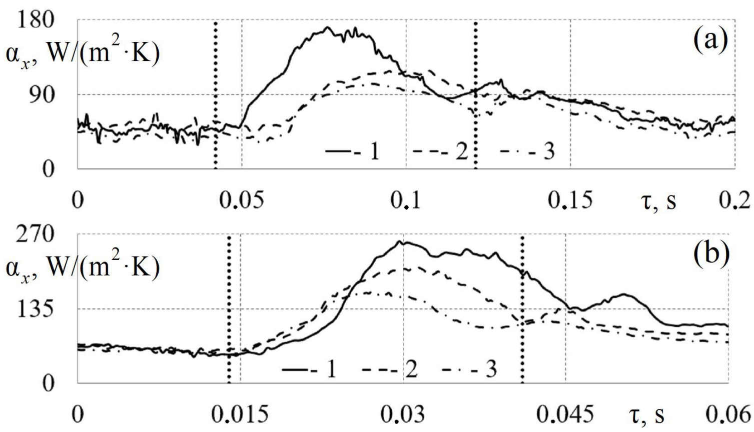

Figure 8. Dependences of the local (l_x = 100 mm) heat transfer coefficient α_x in the intake system of a piston engine on time τ for crankshaft speeds of 600 rpm (**a**) and 1800 rpm (**b**) for different diameters of the intake channel: 1—d = 26 mm; 2—d = 32 mm; 3—d = 40 mm. The vertical lines indicate the opening and closing times of the intake valve.

The change in the intensity of turbulence depending on the rotational speed and the average air flow rate in intake systems with channels with different diameters is shown in Figure 9.

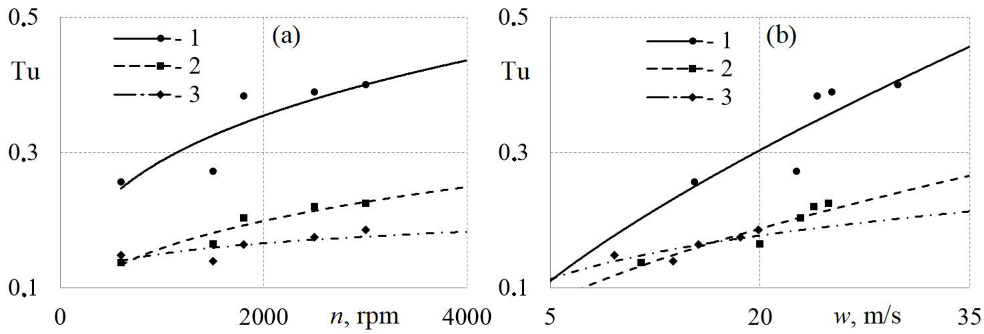

Figure 9. Dependences of the degree of turbulence Tu of the flows on the crankshaft speed n (**a**) and the average flow velocity w (**b**) in the intake system with channels of different diameters: 1—d = 26 mm; 2—d = 32 mm; 3—d = 40 mm.

Figure 9 shows that the change in Tu for the studied configurations of intake systems ranges from 0.1 to 0.45. In this case, the smaller the diameter of the inlet channel, the greater the value of the turbulence intensity. This is due to the fact that the increase in the volume of the intake system smooths out the pulsations in the air flow rate.

The value of Tu has a significant effect on the system's hydraulic resistance, the level of heat transfer, and the gas-dynamic noise of pulsating flows. Therefore, it is necessary to take into account the intensity of flow turbulence in mathematical models, engineering calculations, and engine operation. It is expedient to obtain empirical dependences of Tu on the design (channel diameter) and operation (rotation frequency and average speed) factors in the RICE intake system.

Dependence Tu = f (n) for an intake system with channels of different diameters is described by the following mathematical equation with an error of no more than 6.4%:

$$\mathrm{Tu} = 104.7 \cdot n^{0.3} \cdot d^{-1.77}. \quad (1)$$

This equation is valid for n values in the range from 600 to 3000 rpm and d values in the range from 25 to 40 mm. This type of equation is convenient to use in engineering calculations when designing engine gas exchange systems.

Dependence Tu = f (w) for an intake system with channels of different diameters is described by the following mathematical equation with an error of no more than 6.8%:

$$\mathrm{Tu} = 16.5 \cdot w^{0.56} \cdot d^{-1.25}. \quad (2)$$

This equation is valid for w values in the range from 7 m/s to 35 m/s and d values in the range from 25 to 40 mm. This type of equation is typically used to set up a mathematical model for calculating processes in the intake system.

The flow characteristics of a piston engine for an intake system with channels of different diameters are shown in Figure 10.

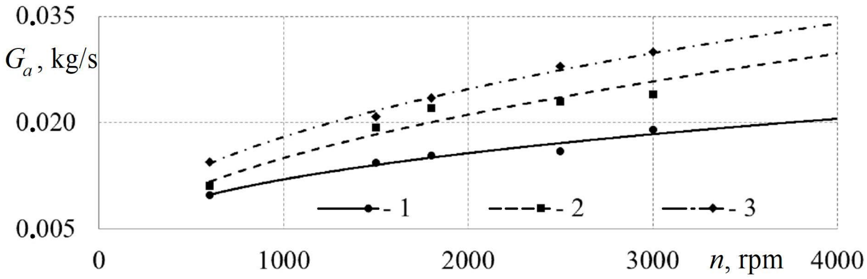

Figure 10. Dependences of the mass air flow G_a on the crankshaft speed n through the intake system with channels of different diameters: 1—d = 26 mm; 2—d = 32 mm; 3—d = 40 mm.

An increase in the intake duct's diameter leads to an increase in air flow through the intake system by 10–18% compared to the basic configuration. This is explained by the fact that an increase in the channel's diameter leads to an increase in the area of the intake system's flow section. However, it should be noted that the growth of flow characteristics through the intake system is not unlimited and is constrained by the value of the flow area of the valve assembly in the cylinder head component. At the same time, a decrease in the diameter of the inlet channel causes a drop in flow characteristics through the inlet system by 5–27% compared to the basic configuration.

Generalised data on heat transfer in the form of dependences of the average heat transfer coefficient in intake systems of different configurations on the crankshaft speed and time are shown in Figure 11. The average heat transfer coefficient α was determined for one control section according to four local data summed up within the intake process (for the period of the open intake valve).

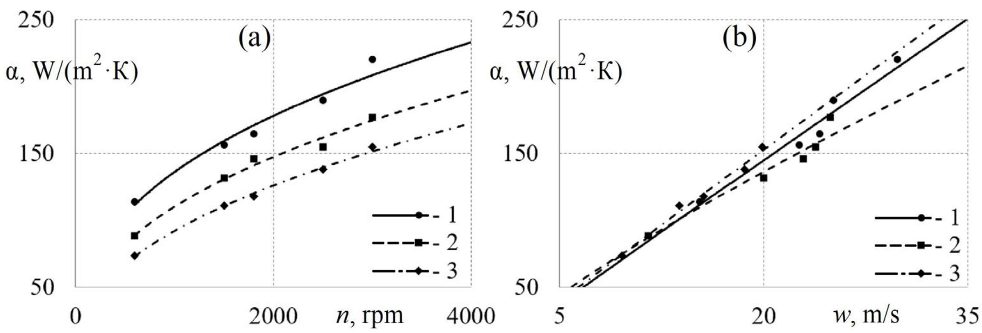

Figure 11. Dependences of the average heat transfer coefficient α on the crankshaft speed n (**a**) and the average flow rate w (**b**) in the intake system with channels of different diameters: 1—d = 26 mm; 2—d = 32 mm; 3—d = 40 mm.

Figure 11a shows that an increase in the diameter of the inlet channel causes a decrease in the heat transfer coefficient by 11–19% compared to the basic configuration. Conversely, a decrease in the channel diameter leads to an increase in α by 12–23%. The presentation of data on the level of heat transfer in the form of a function $\alpha = f\ (w)$ significantly changes the physical phenomenon (Figure 11b). In this case, the heat transfer coefficient for the basic intake system has the lowest values, and a decrease or increase in the channel diameter leads to an increase in α of up to 20%. Thus, by changing the intake system's design, it is possible to control the gas-dynamic and heat exchange characteristics of pulsating flows and optimise the performance of a piston engine according to the operating mode.

The intensity of heat transfer in a piston engine's intake system influences the amount of heating of the working medium, the level of thermal stresses, the coefficient of charge, and the specific power. The use of reliable data on the heat transfer coefficient is an important component in the calculation and design of RICE gas exchange systems. Therefore, the mathematical description of experimental data on the change in the heat transfer coefficient of pulsating flows in the engine intake system from design and operating factors remains a relevant objective for the development of science and technology.

The dependence $\alpha = f\ (n)$ for an intake system with channels of different diameters is described by the following mathematical expression with an error of no more than 8.5%:

$$\alpha = 2287 \cdot n^{0.4} \cdot d^{-0.8}. \tag{3}$$

This equation is valid for n values in the range from 600 to 3000 rpm and d values in the range from 25 to 40 mm. This form of the equation is convenient for use in engineering calculations at the design stage of a piston engine.

The $\alpha = f\ (w)$ dependence for an intake system with channels of different diameters is described by the following mathematical equation with an error of no more than 8.8%:

$$\alpha = 56.6 \cdot w^{0.95} \cdot d^{0.27}. \tag{4}$$

This equation is valid for w values in the range from 7 m/s to 35 m/s and d values in the range from 25 to 40 mm. This form of the equation is convenient for engineering calculations and mathematical modelling as a check for existing results.

Integral data on the heat transfer of pulsating air flows in the intake systems in the form of dimensionless functions $\mathrm{Nu} = f\ (\mathrm{Re})$ are shown in Figure 12.

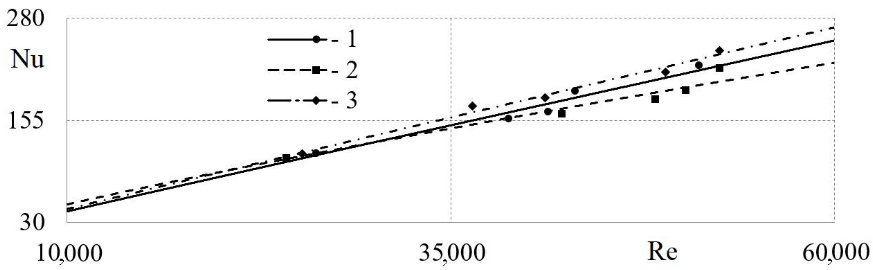

Figure 12. Dependences of the Nusselt number Nu on the Reynolds number Re in the intake system with channels of different diameters: 1—d = 26 mm; 2—d = 32 mm; 3—d = 40 mm.

It has been established that the value of the Nusselt number for the basic intake system has the lowest values, and a decrease or increase in the channel's diameter leads to an increase in Nu of up to 18%.

The dependence $\mathrm{Nu} = f\ (\mathrm{Re})$ for an intake system with channels of different diameters can be mathematically described in the form (with an error of no more than 10%) as follows:

$$\mathrm{Nu} = 101.5 \cdot \mathrm{Re}^{0.97} \cdot d^{0.15} \tag{5}$$

This equation is valid for Re values in the range from 15,000 to 60,000 and d values in the range from 25 to 40 mm. The presented dimensionless equation is convenient to use in mathematical models to improve their accuracy.

4. Applied Data Value

In order to emphasise the importance of the effect of the intake system channel's diameter on RICE performance, the mathematical modelling of the prototype engine's thermodynamic cycle was carried out in the Diesel-RK programme. The main engine parameters for modelling are given in Section 2 of the article. The simulation was performed for four inlet port diameters equal to 20 mm, 32 mm, 40 mm, and 50 mm. The other parameters of the mathematical model remained unchanged. Before the numerical study, the basic mathematical model was tuned by comparing the simulation results with the engine nameplate data from the operation manual. The comparison was based on four parameters (power, torque, fuel flow, average cycle pressure). The differences between the simulation results and datasheet specifications did not exceed ±2%.

An additional comparison of simulation data, laboratory studies, and bench tests were performed to confirm the adequacy of the mathematical model in Diesel-RK (Figure 13). Figure 13 shows that there is a visual match between the experimental data and simulation results. It has been established that the standard deviation of the calculated values from the experimental results is no more than 8.1%. Such a coincidence of data indicates the adequacy of the mathematical model and confirms the possibility of its use in the framework of this scientific work.

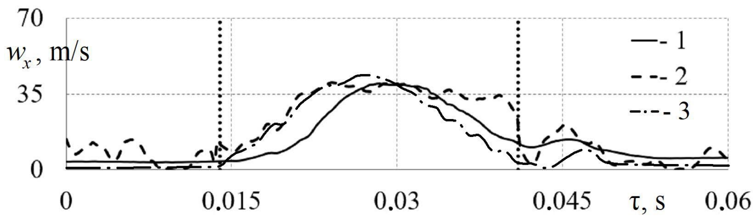

Figure 13. Dependences of the local air flow velocity w_x in the intake systems of the engine laboratory model (1), gasoline RICE (2), and mathematical model (3) on time τ for a crankshaft speed of 1800 rpm and for d = 32 mm. The vertical lines indicate the opening and closing times of the intake valve.

The influence of the intake duct diameter on the rated power N and the maximum torque M can be evaluated from the diagrams shown in Figure 14. Figure 14a shows that a change in the inlet channel's diameter causes both an increase in the rated power (within 1%) and a decrease (within 4.5%). The intake port diameter has a similar effect on the maximum torque (Figure 14b). So, there is an increase in M by up to 1% at d = 20 mm; in contrast, a decrease in M by 0.5–1.5% can be recorded at d = 40 mm and d = 50 mm. This confirms the importance of correctly predicting gas dynamics and heat transfer in a gas exchange system to obtain optimal RICE performance.

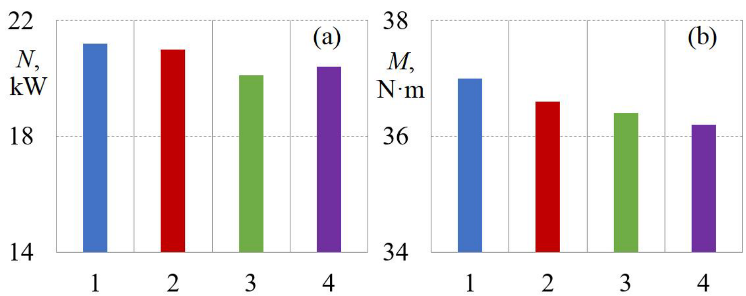

Figure 14. Diagrams of nominal power N (**a**) at n = 5600 rpm and maximum torque M (**b**) at n = 4000 rpm for an intake system with channels of different diameters: 1—d = 20 mm; 2—d = 32 mm; 3—d = 40 mm; 4—d = 50 mm.

The effect of intake port diameter on engine efficiency is shown in Figure 15a. It has been established that the use of an inlet channel with a diameter of 20 mm leads to a slight decrease in the specific flow rate by 0.3% compared to the basic configuration. At the same time, an increase in diameter causes a noticeable increase in fuel flow by up to 1.5%.

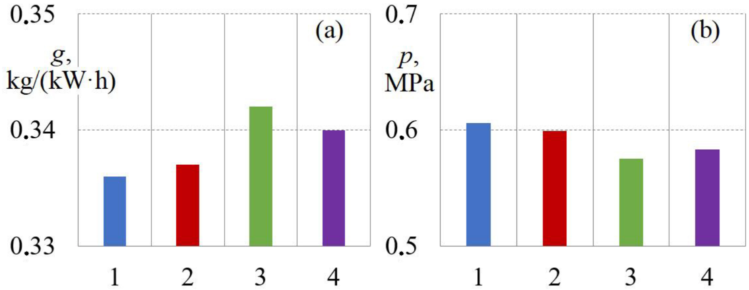

Figure 15. Diagrams of values of specific fuel flow g (**a**) and average cycle pressure p (**b**) of the engine in nominal mode for an intake system with channels of different diameters: 1—d = 20 mm; 2—d = 32 mm; 3—d = 40 mm; 4—d = 50 mm.

The cycle's average pressure characterises both the perfection of the operating cycle and the level of mechanical tension in the engine's main parts (Figure 15b).

Figure 15b shows that reducing the inlet diameter to 20 mm causes an increase in the average cycle pressure by 1.1% compared to the base value. At the same time, an increase in the channel diameter, on the contrary, leads to a drop in the cycle's average pressure of up to 4.5%. Accordingly, there is an optimal diameter of the inlet channel, which provides high-quality filling of the cylinder and the best conditions for the mixture formation of the fuel-air mixture. The search for the optimum should be carried out on the basis of mathematical modelling (with support for artificial intelligence algorithms). The mathematical model needs to be verified.

The data obtained indicate the need for a detailed account of the gas-dynamic and heat exchange characteristics of the flows and the configuration of the intake system in order to achieve the maximum efficiency of a piston engine. This can be achieved through the use of well-established mathematical models at the design stage and the refinement of the engine design with artificial intelligence algorithms at the operation stage.

The inlet channel's diameter has a significant impact on a piston engine's environmental performance (Figure 16). An increase in the diameter of the inlet channel to 40 mm leads to a decrease in NOx emissions in the engine's exhaust gas by 2.5% compared to the basic intake system. The minimum amount of NOx emissions (at d = 40 mm) is explained by the decrease in the maximum and average temperatures in the combustion chamber (highest fuel consumption) during the combustion of the working fluid due to the most favourable conditions for the mixture formation process in this case. The presence of an enhanced cooling system can reduce NOx emissions in the exhaust gases of a gasoline engine.

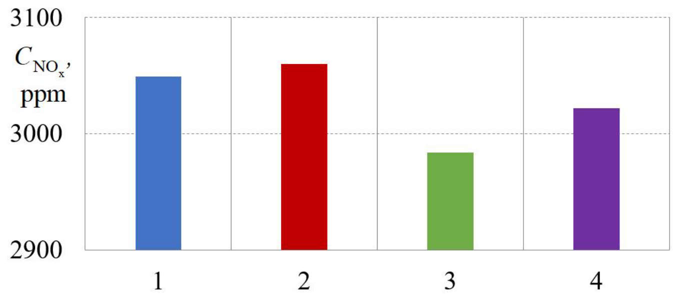

Figure 16. Diagrams of NOx concentration values in the exhaust gases of the engine at nominal mode for the intake system with channels of different diameters: 1—d = 20 mm; 2—d = 32 mm; 3—d = 40 mm; 4—d = 50 mm.

An analysis of the simulation results shows the following:

- the inlet channel's diameter affects the operational and environmental performance of a piston engine;
- it is impossible to unambiguously determine the optimal value of the diameter of the inlet channel, since some engine parameters improve, while others deteriorate;
- accurate mathematical models and artificial intelligence algorithms can significantly increase the level of engine design and improve the prediction of its performance.

5. Conclusions

The conducted research produced the following results.

1. A set of experimental data has been obtained on the change in the local velocity and local heat transfer coefficient of pulsating air flows in an intake system with channels of different diameters, as applied to a car piston engine.
2. It has been established that the intake channel's diameter has a significant effect on the input-output characteristics through the piston engine's intake system: the larger the diameter of the channel, the greater the G_a air flow through the system. The change in G_a ranges from 5% to 27%.
3. The influence of the inlet channel's diameter on the intensity of turbulence of pulsating flows in the inlet system is shown. An increase in the channel diameter causes a decrease in Tu in the RICE exhaust system. A mathematical description of the dependence of the intensity of turbulence on regime factors (speed of rotation of the crankshaft and the average speed of air flow) and the inlet channel's diameter is proposed.
4. The influence of the inlet channel's diameter on the level of heat transfer of pulsating air flows in the inlet system was discovered. It is shown that for the basic configuration of the intake system (d = 32 mm), the values of the Nusselt number have the lowest values. A mathematical description of the dependence of the heat transfer coefficient on the crankshaft speed, the average air flow rate, and the inlet channel's diameter is proposed. An empirical equation for the function Nu = f (Re) is also obtained.
5. Based on the numerical simulation of a reciprocating engine's thermodynamic cycle, an assessment of the operational and environmental performance of RICE with an intake system with channels of different diameters was conducted. A change in power, torque, specific fuel flow, average cycle pressure, and NOx emissions for intake ports with different diameters is shown.
6. The obtained data on the gas dynamics and heat transfer of pulsating gas flows in intake systems can be useful for improving the accuracy of mathematical models and developing efficient and accurate control systems for gas exchange processes in reciprocating engines.
7. Lines for further research are to expand the boundary conditions of the experiment (channel diameter, rotational speed, engine dimension) and verification of laboratory data through tests on an operating engine.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

RICE	reciprocating internal combustion engine
ADC	analogue-to-digital converter
TDC	top dead centre
BDC	bottom dead centre
w	flow velocity, m/s
w_x	local flow velocity, m/s
α	heat-transfer factor, W/(m^2·K)
α_x	local heat transfer coefficient, W/(m^2·K)
p_o	barometric pressure, kPa
p	static pressure, MPa
t	temperature, °C
d	pipeline diameter, mm
l_x	linear dimension, mm
Tu	turbulence intensity
G_a	mass air flow, kg/s
N	engine power, kW
M	engine torque, N·m
g	specific fuel consumption, kg/(kW·h)
C_{NOx}	NOx concentration in exhaust gases, ppm
n	engine crankshaft speed, rpm
τ	time, s
Nu	Nusselt number
Re	Reynolds number
Sh	Strouhal number

References

1. Reitz, R.D.; Ogawa, H.; Payri, R.; Fansler, T.; Kokjohn, S.; Moriyoshi, Y.; Agarwal, A.K.; Arcoumanis, D.; Assanis, D.; Bae, C.; et al. IJER editorial: The future of the internal combustion engine. *Int. J. Engine Res.* **2020**, *21*, 3–10. [CrossRef]
2. Guzzella, L.; Onder, C. *Introduction to Modeling and Control of Internal Combustion Engine Systems*; Springer: Berlin/Heidelberg, Germany, 2010; 362p.
3. Lumley, J.L. *Engines, An Introduction*; Cambridge University Press: Cambridge, UK, 1999; 272p.
4. Plotnikov, L.V. Unsteady gas dynamics and local heat transfer of pulsating flows in profiled channels mainly to the intake system of a reciprocating engine. *Int. J. Heat Mass Transf.* **2022**, *195*, 123144. [CrossRef]
5. Pranoto, S.; Ubaidillah, A.; Lenggana, B.W.; Budiana, E.P.; Wijayanta, A.T. Fluid Flow Analysis at Single and Dual Plenum Intake Manifolds to Reduce Pressure Drops Using Computational Approach. *J. Adv. Res. Fluid Mech. Therm. Sci.* **2022**, *97*, 1–12. [CrossRef]
6. Zhang, S.; Li, Y.; Wang, S.; Zeng, H.; Liu, J.; Duan, X.; Dong, H. Experimental and numerical study the effect of EGR strategies on in-cylinder flow, combustion and emissions characteristics in a heavy-duty higher CR lean-burn NGSI engine coupled with detail combustion mechanism. *Fuel* **2020**, *276*, 118082. [CrossRef]
7. Zhao, D.; An, Y.; Pei, Y.; Shi, H.; Wang, K. Numerical study on the asymmetrical jets formation from active pre-chamber under super-lean combustion conditions. *Energy* **2023**, *262*, 125446. [CrossRef]
8. Yuan, C.; Li, S.; Qin, Z.; Lu, J.; Peng, S. A multi-process coupling study of scavenging pressure effect on gas exchange of a linear engine. *Appl. Therm. Eng.* **2022**, *217*, 119254. [CrossRef]
9. Yin, S.; Ni, J.; Fan, H.; Shi, X.; Huang, R. Study on Correction Method of Internal Joint Operation Curve Based on Unsteady Flow. *Appl. Sci.* **2022**, *12*, 11943. [CrossRef]
10. Marelli, S.; Capobianco, M.; Zamboni, G. Pulsating flow performance of a turbocharger compressor for automotive application. *Int. J. Heat Fluid Flow* **2014**, *45*, 158–165. [CrossRef]
11. Leng, L.; Qiu, H.; Li, X.; Zhong, J.; Shi, L.; Deng, K. Effects on the transient energy distribution of turbocharging mode switching for marine diesel engines. *Energy* **2022**, *249*, 123746. [CrossRef]
12. Liu, Z.; Liu, J. Investigation of the Effect of Altitude on In-Cylinder Heat Transfer in Heavy-Duty Diesel Engines Based on an Empirical Model. *J. Energy Resour. Technol. Trans. ASME* **2022**, *144*, 112303. [CrossRef]
13. Nie, X.; Bi, Y.; Liu, S.; Shen, L.; Wan, M. Impacts of different exhaust thermal management methods on diesel engine and SCR performance at different altitude levels. *Fuel* **2022**, *324*, 124747. [CrossRef]
14. Ma, F.; Yang, W.; Wang, Y.; Xu, J.; Li, Y. Experimental research on scavenging process of opposed-piston two-stroke gasoline engine based on tracer gas method. *Int. J. Engine Res.* **2022**, *23*, 1969–1980. [CrossRef]
15. Mazuro, P.; Kozak, D. Experimental investigation on the performance of the prototype of aircraft Opposed-Piston engine with various values of intake pressure. *Energy Convers. Manag.* **2022**, *269*, 116075. [CrossRef]

16. Suhas, B.G.; Rajesh, R.; Chidanand, K.M.; Kiran, K.U.; Shivaprasad, K.V. Numerical analysis on performance evaluation of a flat plate louvered fin heat exchanger. *J. Eng. Sci. Technol.* **2022**, *17*, 1867–1879.
17. Yoon, W.; Kim, J.; Chung, C.; Park, J. Numerical study on prediction of icing phenomena in intake system of diesel engine: Operating conditions with low-to-middle velocity of inlet air. *Energy* **2022**, *248*, 123569. [CrossRef]
18. Li, Z.; Wang, Z.; Mo, H.; Wu, H. Effect of the Air Flow on the Combustion Process and Preheating Effect of the Intake Manifold Burner. *Energies* **2022**, *15*, 3260. [CrossRef]
19. Wang, T.; Li, W.; Jia, M.; Liu, D.; Qin, W.; Zhang, X. Large-eddy simulation of in-cylinder flow in a DISI engine with charge motion control valve: Proper orthogonal decomposition analysis and cyclic variation. *Appl. Therm. Eng.* **2015**, *75*, 561–574. [CrossRef]
20. Shah, S.S.; Singh, K.; Martin, L.J.; Jerome Stanley, M. Design, Development, and Validation of an Intake System for an FSAE Racecar. In *Energy and Exergy for Sustainable and Clean Environment*; Green Energy and Technology Book Series; Springer: Singapore, 2023; pp. 401–413.
21. Luo, K.; Huang, Y.; Han, Z.; Li, Y.; Shi, Y.; Liu, W.; Tang, C. Low-speed performance compensation of a turbocharged natural gas engine by intake strategy optimization. *Fuel* **2022**, *324*, 124748. [CrossRef]
22. Gangaraju, Manjunatha Babu, N.S.; Mohan Kumar, K. Study on structural stability of intake manifold valve through numerical analysis. *Int. J. Ambient. Energy* **2022**, *43*, 6981–6991. [CrossRef]
23. Plotnikov, L.V. Experimental research into the methods for controlling the thermal-mechanical characteristics of pulsating gas flows in the intake system of a turbocharged engine model. *Int. J. Engine Res.* **2022**, *23*, 334–344. [CrossRef]
24. Jia, B.; Smallbone, A.; Mikalsen, R.; Shivaprasad, K.V.; Roy, S.; Roskilly, A.P. Performance Analysis of a Flexi-Fuel Turbine-Combined Free-Piston Engine Generator. *Energies* **2019**, *12*, 2657. [CrossRef]
25. Perceau, M.; Guibert, P.; Guilain, S. Zero-dimensional turbulence modeling of a spark ignition engine in a Miller cycle «Dethrottling » approach using a variable valve timing system. *Appl. Therm. Eng.* **2021**, *199*, 117535. [CrossRef]
26. Iurk, M.A.; Och, S.H.; Moura, L.M.; Mariani, V.C.; Domingues, E. Maximizing volumetric efficiency using stochastic optimization techniques for internal combustion engines. *Appl. Therm. Eng.* **2021**, *199*, 117603. [CrossRef]
27. Jung, J.; Song, S.; Hur, K.B. Numerical study on the effects of intake valve timing on performance of a natural gas-diesel dual-fuel engine and multi-objective Pareto optimization. *Appl. Therm. Eng.* **2017**, *121*, 604–616. [CrossRef]
28. Song, Y.; Xu, Y.; Cheng, X.; Wang, Z.; Zhu, W.; Fan, X. Using a Genetic Algorithm to Achieve Optimal Matching between PMEP and Diameter of Intake and Exhaust Throat of a High-Boost-Ratio Engine. *Energies* **2022**, *15*, 1607. [CrossRef]
29. Shao, Y.E.; Hu, Y.-T. Using Machine Learning Classifiers to Recognize the Mixture Control Chart Patterns for a Multiple-Input Multiple-Output Process. *Mathematics* **2020**, *8*, 102. [CrossRef]
30. Sidorov, D. Preface to "Model Predictive Control and Optimization for Cyber-Physical Systems". *Mathematics* **2023**, *11*, 1004. [CrossRef]
31. Gordon, D.; Norouzi, A.; Blomeyer, G.; Bedei, J.; Aliramezani, M.; Andert, J.; Koch, C.R. Support vector machine based emissions modeling using particle swarm optimization for homogeneous charge compression ignition engine. *Int. J. Engine Res.* **2023**, *24*, 536–551. [CrossRef] [PubMed]
32. Seo, J.; Park, S. Optimizing model parameters of artificial neural networks to predict vehicle emissions. *Atmos. Environ.* **2023**, *294*, 119508. [CrossRef]
33. Shirvani, S.; Shirvani, S.; Jazayeri, S.A.; Reitz, R. Optimization of the exergy efficiency, exergy destruction, and engine noise index in an engine with two direct injectors using NSGA-II and artificial neural network. *Int. J. Engine Res.* **2023**, *24*, 579–594. [CrossRef]
34. Gordon, D.; Wouters, C.; Wick, M.; Xia, F.; Lehrheuer, B.; Andert, J.; Koch, C.R.; Pischinger, S. Development and experimental validation of a real-time capable field programmable gate array–based gas exchange model for negative valve overlap. *Int. J. Engine Res.* **2020**, *21*, 421–436. [CrossRef]
35. Guner, E.; Kaleli, A.; Bakirci, K.; Ceviz, M.A. Development of optimal diesel injection strategy based on the prediction of performance and emissions using deep neural network. *Int. J. Engine Res.* **2023**, *24*, 567–578. [CrossRef]
36. Rayasam, S.H.; Qiu, W.; Rimstidt, T.; Shaver, G.M.; Alstine, D.G.V.; Graziano, M. Control-oriented modeling, validation, and interaction analysis of turbocharged lean-burn natural gas variable speed engine. *Int. J. Engine Res.* **2023**, *24*, 738–754. [CrossRef]
37. Plotnikov, L.; Plotnikov, I.; Osipov, L.; Slednev, V.; Shurupov, V. An Indirect Method for Determining the Local Heat Transfer Coefficient of Gas Flows in Pipelines. *Sensors* **2022**, *22*, 6395. [CrossRef] [PubMed]
38. Kuleshov, A.S. *Model for Predicting Air-Fuel Mixing, Combustion and Emissions in DI Diesel Engines over Whole Operating Range*; SAE Paper, 2005-01-2119; SAE International: Warrendale, PA, USA, 2005.
39. Kuleshov, A.S. *Multi-Zone DI Diesel Spray Combustion Model for Thermodynamic Simulation of Engine with PCCI and High EGR Level*; SAE Paper, 2009-01-1956; SAE International: Warrendale, PA, USA, 2009.
40. Grigoriev, M.M.; Kuz'min, V.V.; Fafurin, A.V. Classification of pulsating turbulent flows. *J. Eng. Phys. Thermophys.* **1990**, *59*, 725–735.
41. Plotnikov, L.V. 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.* **2022**, *26*, 365–376. [CrossRef]