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THE MODEL OF THE EXHAUST GAS DUCT FLOW OF THE MARINE 4-STROKE DIESEL ENGINE

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Abstract

The manuscript presents the model of the exhaust gas flow through the exhaust gas duct of the marine 4-stroke engine. Presented model are computational fluid dynamic model based on dimensions and the construction of the real exhaust gas duct. The measurement parameters from real object are used to the model validation. The simulation of the exhaust gas duct throttling by rotational throttling plate was done. Obtained calculation results allow to determination of the exhaust gas mass flow for the simulated flow characteristics. The model of turbulence flow was taken into account. The gravity forces and the heat transfer phenomena were neglected. Obtained calculation results are qualitatively consistent with results obtained from literature. The analyze of the velocity distribution in the exhaust gas duct allows to conclusion that the changes of the angular position of the throttling plate causes significant disturbances in the exhaust gas flow. The result of this is the decrease of the exhaust gas flow. Additional purpose of the manuscript was approximation of the obtained results of the exhaust gas flow for different angular positions of the throttling plate. Obtained polynomial function may be useful tool to modeling the combustion process in the engine cylinders for the different flow characteristics of the exhaust gas duct. The calculation results allow to determination the mass flow of the exhaust gas with mean error equal 11%.

Keywords: *marine diesel engine, exhaust gas composition, toxic emission, CFD model, exhausts gas duct throttling*

1. Introduction

4-stroke diesel engines are commonly used sources of the mechanical energy in the land and the marine applications. Unfortunately they are the sources of the gaseous toxic compounds also. Mentioned compounds are products of the hydrocarbon fuels in air. According to regulations of the Annex VI to MARPOL Convention [11] all marine engines with nominal power output above 130kW must apply the nitric oxides emission limits. Emission must be calculated according to regulations from “Technical code on control of emission of nitrogen oxides from marine diesel engines” [12] and the ISO-8178 standard regulations [3]. According to European Commission regulation [2] the diesel engines operated in the on-road vehicles must apply the emission limits of carbon oxides, hydrocarbons and solid particles.

Delimitation of the toxic gaseous compounds emission requires direct measurements of the fractions of the mentioned compounds in the exhaust gas during the engine operation with specified loads. Quantity of the emission of the toxic compounds requires the calculation of the mass flow of the exhaust gas. Three methods are acceptable:

- direct measurement of the exhaust gas flow,

- measurement of the fuel consumption and the air flow to the engine and calculation of the exhaust gas flow,
- measurement of the fuel consumption and calculation of the exhaust gas flow according to carbons balance method [3].

Direct measurement of the exhaust gas flow in the case of large, marine diesel engines is very difficult and not precise. Therefore, often applied method is calculation of the exhaust gas flow by carbons balance method. Disadvantage of this method is the calculation error caused by “a priori” assumed the chemical composition of the fuel.

The diesel engines operations causes deterioration of its technical state. Effect of this are the changes in the organization of the combustion process in the engine cylinders and changes in the emission of the toxic compounds. The solid particles emission causes particles deposition on the surfaces of the exhaust gas duct. In [5] author presents the results of the laboratory research about influence of the exhaust gas duct throttling on the composition of the exhaust gas. According to these results the throttling of the exhaust gas duct causes significant changes of the carbon oxide emission. Obtained results allow to only qualitatively analyzing. The reason of this lack of possibility of the determination of influence of the exhaust gas duct throttling on the exhaust gas flow. According to this the 3D model of the exhaust gas flow was prepared. The method applied in proposed model is Computational Fluid Dynamic (CFD).

2. Laboratory research

The chosen object of research is 3-cylinder, four-stroke, turbocharged, laboratory engine. The engine is loaded by a generator, electrically connected to the water resistance. During tests the engine was fuelled by diesel oil and operated at a constant speed, equal to 750rpm. The engine load and speed, parameters of the turbocharger, systems of cooling, fuelling, lubricating, and air exchange were measured. Pressure, temperature and humidity of air were recorded by laboratory equipment also. All mentioned results were recorded with a sampling time of 1 second. The scheme of the laboratory stand is presented in [4] and the engine parameters are presented in Tab.1.

Tab. 1. The laboratory engine parameters

Parameter	Value	Unit
Max. electric power	250	kW
Rotational speed	750	rpm
Cylinder number	3	–
Cylinder diameter	250	mm
Stroke	300	mm
Compression ratio	12,7	–

The experimental study consists of 3 stages of 3 observations with simulations of different malfunctions of the exhaust gas duct. During each start of the observation, the engine was loaded to maximum load equal 250kW, and, after stabilizing the temperature of the exhaust gas behind the turbine, the engine operating parameters were recorded for 3 to 5 minutes. After this, the load of the engine was decreased by 10kW and, after stabilizing the temperature of the exhaust gas behind the turbine, the engine operating parameters were recorded again. The observation was continued with loads up to 50kW. The engine did not work with a load of 190kW due to resonance vibrations.

Stages of experiment were set as follows:

- the first stage during the operation of the engine assumed as “working properly”,

– the second stage during the operation of the engine with the throttling of the cross section area of the exhaust gas duct by changing the barrier angle mounted in the exhaust gas duct behind the turbine by 21 degrees,
– the third stage during the operation of the engine with the throttling of the cross section area of the exhaust gas duct by changing the barrier angle mounted in the exhaust gas duct behind the turbine by 71 degrees.

The exhaust gas duct throttling simulation consisted of changing the angle of the throttling barrier mounted in the exhaust gas duct behind the turbine. Scheme of the exhaust gas duct and the prepared 3D model are presented in Fig.1.

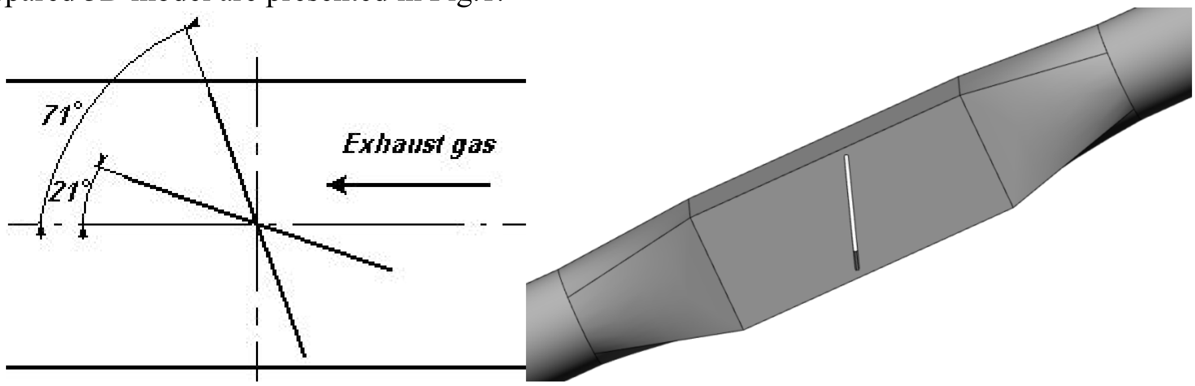

Fig.1. Scheme of the exhaust gas duct and the 3D model

3. CFD model

Obtained laboratory research results and the geometric dimensions of the exhaust gas duct allow preparing the exhaust gas flow model behind the turbine. Throttling of the exhaust gas duct by the rotating plate causes the decrease of the cross section area of the exhaust gas duct and the changes in the flow characteristic, resulting the changes of the duct geometry. The result of this is intensity of turbulence phenomena in the exhaust gas flow.

According to the mentioned purpose the modelling of the exhaust gas flow through the exhaust gas duct was conducted. Chosen method of modelling was Computational Fluid Dynamic (CFD) method.

The used software to CFD conduction was AVL Fire. The exhaust gas duct construction was transferred and meshed to the pre-processor of the AVL Fire package. The cubic mesh with the minimum dimension equal 2,5 mm was chosen. The area of the rotating plate was re-meshed to the minimum dimension equal 1mm. The large dimensions of the exhaust gas duct and its axis symmetric construction, only the axis-symmetric half of the exhaust gas duct was modelled. The momentum and the continuity equations with k-zet-f model of turbulence [10], [14] were performed. The energy balance equations, the heat transfer phenomena and the gravity forces were neglected.

The boundary conditions were selected as follows:

– the exhaust gas duct inlet with the ambient temperature and the ambient pressure of the exhaust gas behind turbine,
– the exhaust gas duct outlet with the ambient temperature of the exhaust gas behind the turbine and the environment pressure,
– the axis-symmetry in the axis-symmetry surface.

The maximum number of iterations was set on 3000 and the convergence criteria of the normalized residuals were set. The calculated result, as an extrapolate values of the cross section area of the exhaust gas duct outlet, is mass flow of the exhaust gas.

Obtain the correct results of the calculation depends on specify the quantity of the Prandtl number and the density of the exhaust gas [6], [9]. The exhaust gas is mixture of the gaseous combustion products, the water steam and not combusted in the engine cylinders air. The results of the exhaust gas analyze, obtained from [5] allows to specify the exhaust gas composition.

Basis on the NIST Chemistry Book [11], about the parameters of the gaseous compounds of the exhaust gas in the obtained temperature and pressure ranges, the calculations of the Prandtl number and the density of the exhaust gas were conducted.

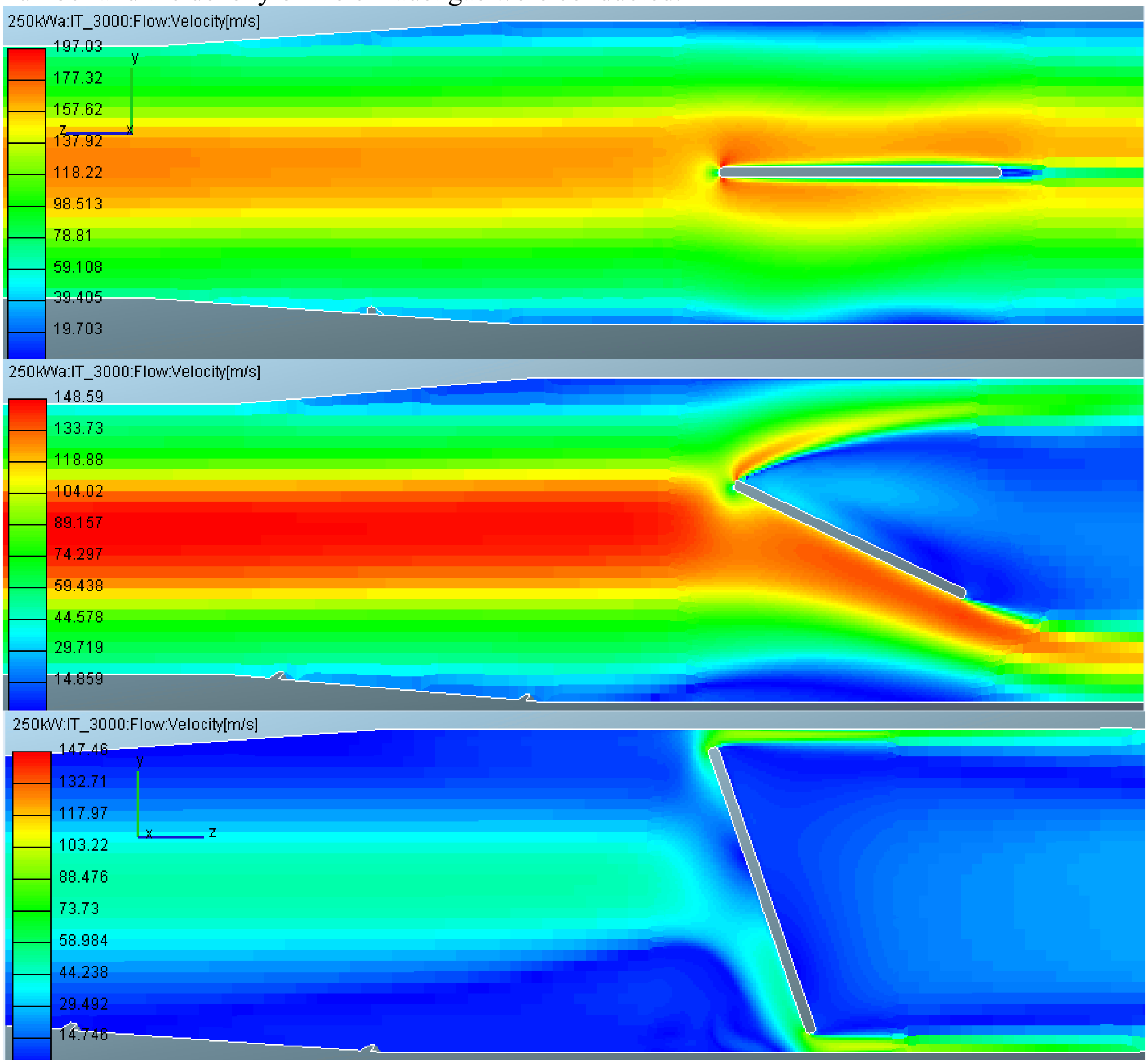

Fig.2. Velocity in the exhaust gas duct for 250kW the engine load

Mentioned calculations were conducted according to the weighted average by the following formula:

$$\mathrm{Pr} = \sum_{i=n}^{i=1} \mathrm{Pr}_i \cdot U_i\,, \tag{1}$$

were:

Pr_i – the Prandtl number for the i-th gaseous compound,

U_i – the fraction of the i-th gaseous compound in the exhaust gas.

The density of the exhaust gas was calculated accordingly to the (1) formula.

4. Results and discussion

Mentioned actions allow to obtain the mass flow of the exhaust gas through the exhaust gas duct of the laboratory engine. The calculations for all considered loads of the engine and all angle positions of the throttling plate presented in [5] are done.

On the Fig.2 the example of calculation results in the form of exhaust gas flow velocity for the engine load equal 250kW and different positions of the throttling plate are presented. Mentioned results are qualitatively representative for all considered loads of the engine. According to presented results horizontal position of the throttling plate disturbs the exhaust gas flow only a small degree. The flow is laminar. Only flow near the duct walls causes the changes on the flow direction. The 21° angle rotation of the throttling plate causes disturbance of the exhaust gas flow. It should be noted that the maximum velocity of the exhaust gas flow in the central point of the cross section decreases by 10%. Further increase of the exhaust gas duct throttling decreases the mass flow of the exhaust gas. The maximum velocity in this condition decreases by 50%. Presented results are qualitatively similar to presented in [1], [8], [13].

Fig.3 presents the results of calculations of the exhaust gas mass flow and measured parameters of the exhaust gas behind the turbine. According to presented results increase of the exhaust gas duct throttling causes the decrease of the mass flow of the exhaust gas.

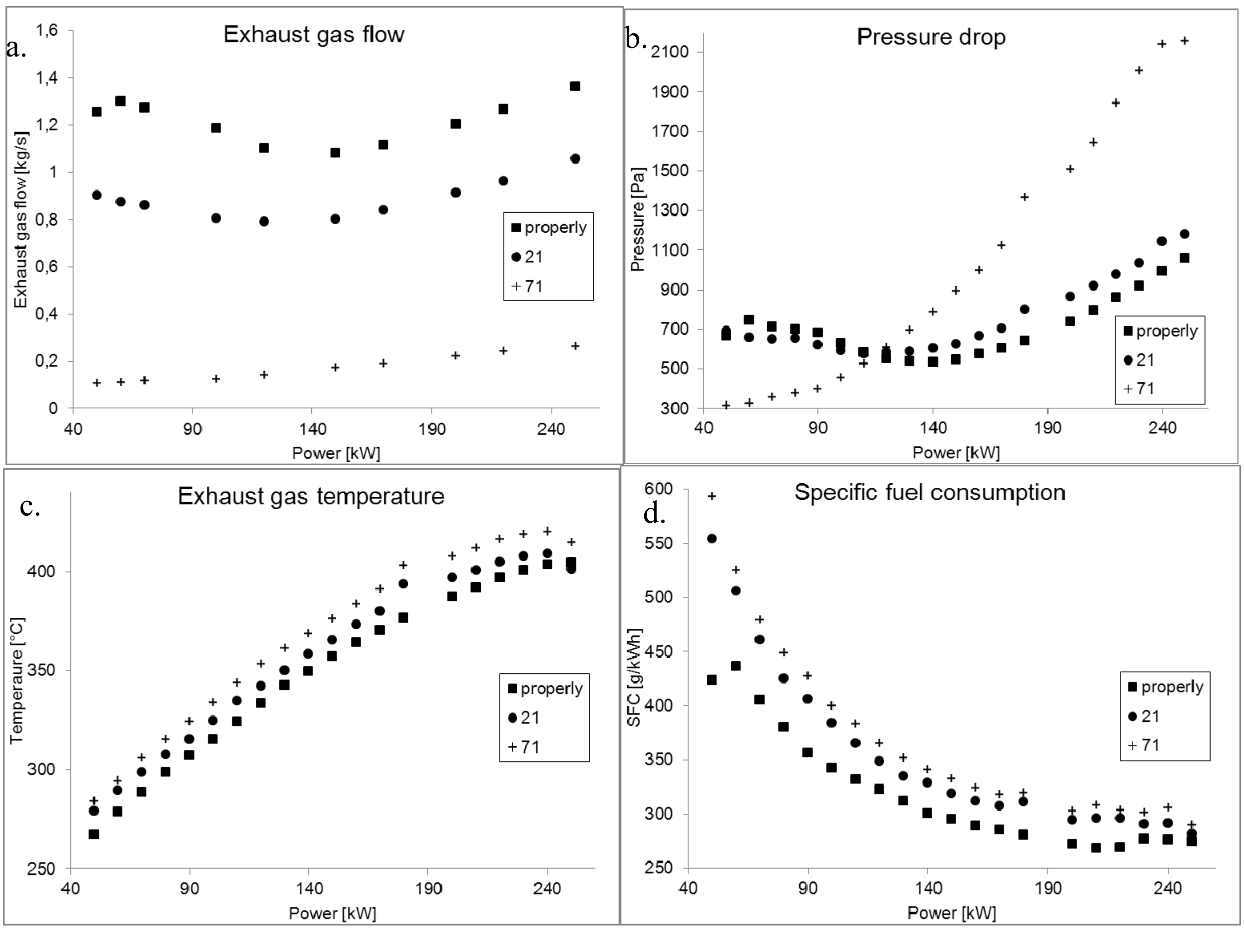

Fig.3. Measured and calculated parameters of the exhaust gas duct

Throttling of the exhaust gas duct decreases the pressure of the exhaust gas behind the turbine and increases its temperature behind the cylinders. Fig.3b and Fig.3c shows changes of the exhaust gas pressure and temperature behind the turbine. According to the presented results, the temperature of the exhaust gas behind turbocharger increases with the increase of both exhaust duct throttling and the load of the engine. The exhaust duct throttling causes abnormalities in the combustion process. Abnormalities of combustion process cause a growth of the fuel consumption. Fig.3d shows specific fuel consumption measured for all considered states of the engine. Throttling of the exhaust gas duct by changing the barrier angle by 21deg. causes average increase of the fuel consumption by 3,7%, and 8,2% for changing the barrier angle by 71deg respectively.

The decrease of the differences of the exhaust gas pressure in the exhaust gas duct causes decrease of the turbocharger performance. The quantity of air delivered to the engine decreases. Simultaneously with this phenomena, the quantity of delivered fuel increases. The effect of this is combustion of the richer mixtures in the cylinders.

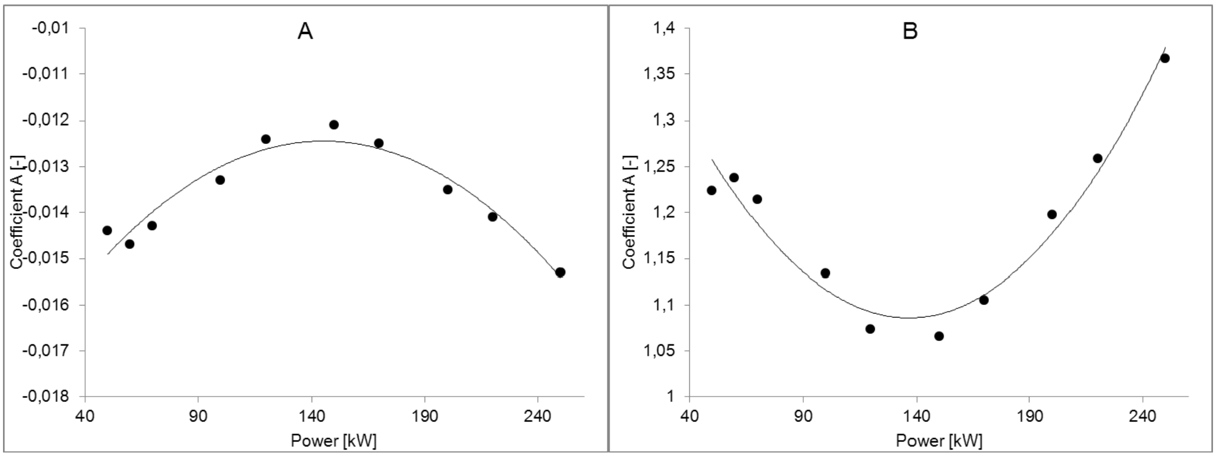

Fig.4. Approximation coefficients for exhaust gas duct flow

The second goal of this research was approximation of the mass flow through the exhaust gas duct in accordance to different position of the throttling plate. Mentioned approximation may be useful tool to modelling the combustion processes in the engine cylinders in the different than laboratory conditions.

Fig.3 presents the linear dependence between the exhaust gas mass flow and the angular position of the throttling plate of the engine in the constant rotational speed. According to this the approximation of this dependence is the linear function as follows:

$$q = A \cdot An + B, \tag{2}$$

where:

q – the mass flow in [kg/s],
An – the angle position of the throttling plate [°],
A, B – coefficients of the linear function.

Change of the engine output power causes changing the values of the mentioned coefficients “A” and “B”. Fig.4 presents the changes of the coefficients values in function of the engine power. The black dots presented the measured points. According to presented results the values of both “A” and “B” coefficients may to be approximated by a second order polynomial, according to the following formulas:

$$A = a1 \cdot P^2 + a2 \cdot P + a3, \tag{3}$$

$$B = b1 \cdot P^2 + b2 \cdot P + b3, \tag{4}$$

where:

P – the power output of the laboratory engine [kW],
a1 ÷ a3, b1 ÷ b3 – the coefficients of the second order polynomials [-].

Presented analyse allows to select the values of values of coefficients from "a1" to "b3" for the considered laboratory stand. Mentioned values are presented in Table 2. The results of calculation the "A" and "B" coefficients with use of values from the Tab.2 are presented in Fig.4 by continuous line.

Tab.2. The coefficients values of the approximation function

Coefficient	a1	a2	a3	b1	b2	b3
Value [-]	-3E-07	8E-05	0,0182	2E-05	0,0062	1,5124

Presented results allow calculating the quantity of the exhaust gas mass flow for different values of the exhaust gas duct throttling in the range from the 0 to the 71° of the angular position of the throttling plate area without direct measurement. The maximum error of obtained approximation compared to measured values not excided 11%.

5. Conclusions

The main purpose of the presented manuscript is determination of the flow characteristic of the exhaust gas duct of the marine 4-stroke diesel engine. The simulation of the exhaust gas duct throttling by rotational throttling plate was done. The 3-dimensional flow model witch use of CFD method is applied. Obtained calculation results allow to determination of the exhaust gas mass flow for the simulated flow characteristics. The model of turbulence flow was taken into account. The gravity forces and the heat transfer phenomena were neglected. Obtained calculation results are qualitatively consistent with results obtained from literature. The analyze of the velocity distribution in the exhaust gas duct allows to conclusion that the changes of the angular position of the throttling plate causes significant disturbances in the exhaust gas flow. This causes the eddies creation and back flows. The result of this is the decrease of the exhaust gas flow.

Additional purpose of the manuscript was approximation of the obtained results of the exhaust gas flow for different angular positions of the throttling plate. Obtained polynomial function may be useful tool to modeling the combustion process in the engine cylinders for the different flow characteristics of the exhaust gas duct. The calculation results allow to determination the mass flow of the exhaust gas with mean error equal 11%. The author's assessment is that obtained accuracy is not enough to use in the modeling practice. Therefore, further work is required in this area. May find the following a parametric assessment of the exhaust gas flow phenomena.

Acknowledgments

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