THE MODEL OF THE AIR INLET DUCT FLOW OF THE MARINE 4-STROKE DIESEL ENGINE

Jerzy Kowalski

Gdynia Maritime University
Department of Engineering Sciences
Morska Street 81-87, 81-225 Gdynia, Poland
tel.: +48 58 6901434, fax: +48 58 6901399
e-mail: jerzy95@am.gdynia.pl

Abstract

The manuscript presents the model of the air flow through the air inlet duct of the marine 4-stroke engine. Presented model are computational fluid dynamic modelbased on dimensions and the construction of the real air intake duct. The measurement parameters from real object are used to the model validation. Mentioned measurements of the air flow are conducted by Venturi orifice for different loads of the engine and the different flow characteristics of the air intake duct. The results from computational fluid dynamic model are useful to calibration the orifice by setting the orifice module. The orifice module changes up to 6% of the mean values for all considered loads of the engine and throttling's of the air intake duct. The approximation the flow characteristic for other throttling's of the air intake duct was conducted also. The obtained approximation is useful tool to calculate the air flow to the engine for the different throttling's than measured. Linear dependence between the air mass flow and the power of the engine at the constant engine speed was observed. The throttling of the cross section area of the air intake duct causes changing the characteristic in accordance to a second order polynomial. The maximum error of obtained approximation compared to measured values not excided 4% and mean error for all measured loads and throttling's not exceeded 0.12%.

Keywords: *marine diesel engine, Venturi orifice, air flow, CFD model, air duct throttling*

1. Introduction

The 4-stroke diesel engines are commonly used in the marine applications. The engines are sources for energy to ships propulsion and to the electric power generation.Mentioned energy is taken from combustion fossil fuels in the engine cylinders. The side effect of the combustion process is the emission of the gaseous products of the combustion into the atmosphere. Due to increasing of the air pollution International Maritime Organization (IMO) enforced Annex VI to the MARPOL Convention with "Technical code on control of emission of nitrogen oxides from marine diesel engines" [10, 13]. Mentioned regulations concern only reduces of the nitric oxides (NO_x) and sulfur oxides (SO_x). The increase of the emission of the other gaseous toxic compounds i.e. carbon oxide, carbon dioxide, hydrocarbons, aldehydes and others, is result of the deterioration of the combustion process in the engine cylinders.

One of the factors, restrictive the engine efficiency is a contamination of the air intake duct.It is well known that the dust contained in the air settles during the engine operation on the air intake duct filter, resulting in time the increase of the air pressure difference on the front and behind the air filter. Please note that the dust getting into the combustion chamber is a precursor of the soot and PM emissions. According to results, presented in [7], throttling of cross section area of the air intake duct reduces pressure of the charging air and reduces its temperature. The consequence of this is a reduction of the amount of air supplied to the engine cylinders. Decreasing the amount of air delivered to the engine cylinders causes the combustion process of a rich mixture. This situation promotes the extension of the combustion process in time, which results the increase of the mean in-cylinder pressure. The effect of this is the increase of the exhaust temperature behind the cylinders and the temperature of the exhaust gas behind the turbine. According to obtained results, throttling of the air intake duct changes the specific fuel consumption onlyto small extent. It should be noted that the fuel consumption is a very important parameter from an economic point of view, but in a practical application (e.g. on board use) it is very difficult to measure.

The reduction of the amount of air delivered to the cylinders of the engine is clearly visible in the emission levels. The increase of the dose of fuel delivered to the combustion process increases CO_2 emission. Increasing the throttling of the air intake duct deteriorates combustion conditions in engine cylinders. The effect of this is the increase of the CO emission at low load engine conditions. It is a result of the incompletely burned fractions in exhaust gas.

Presented analyze allows to only qualitatively denomination of changes of the combustion process.It means that such analyze is incomplete. The reason of this difficulties of assessment the quantity of air, delivered to the engine cylinders in the case of the air filter contamination.

It should be noted that measurement of the air flow in a large marine engines is significantly hindered. The direct measurement requires the meaningful constructional modifications of the air intake duct. The simplest and reliable method of direct measurement applied in described research [7] is measurement by Venturi orifice [3, 4, 6, 11, 12]. Mentioned measurement requires calibration [14]. During the measurements should also pay attention to the possibility of cavitation [1] and possibility of changes the flow characteristic of the orifice, due tosubsidence of contamination in the orifice surface [3, 4].

Bearing in mind the listed inconveniences, author carried out direct measurements of the air flow to the 4-stroke diesel engine for the different characteristics of the air intake duct. The Venturi orifice measurement was chosen. The flow characteristic of the orifice was selected by Computational Fluid Dynamic (CFD) method. The next step was approximation of obtained flow results for different throttling's of the air inlet duct.

2. Laboratory research

The chosen object of research is 3-cylinder, four-stroke, turbocharged, laboratory engine. The engine is loaded bya generator, electrically connected to the water resistance. During teststhe engine was fuelled by diesel oil and operated at a constant speed, equal to 750 rpm. 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 [7] and the engine parameters are presented in Tab. 1.

Tab. 1. The laboratory engine parameters

Parameter	Value	Unit
Max. electric power	250	kW
Engine 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 air intake duct. During each start of the observation, the engine was loaded to maximum load equal 250 kW, and, after stabilizing the temperature of the exhaust gas behindthe turbine, the engine operating parameters were recorded for 3 to 5 minutes. After this, the load of the engine was decreased by 10 kW 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 50 kW. The engine did not work with a load of 190 kW due to resonance vibrations.

Stages of experiment were set as follows:
- first stage during the operation of the engine assumed as "working properly",
- second stage during the operation of the engine with cross section area of air intake duct limited by 20%,
- third stage during the operation of the engine with cross section area of air intake ductlimited by 60%.

The air intake duct throttling simulation consisted of inserting throttling flanges to the air intake duct in front ofthe compressor, limiting duct cross section area by 20% and 60% respectively. Scheme of the air intake duct with the Venturi orifice and place of throttling flanges is presented in Fig. 1.

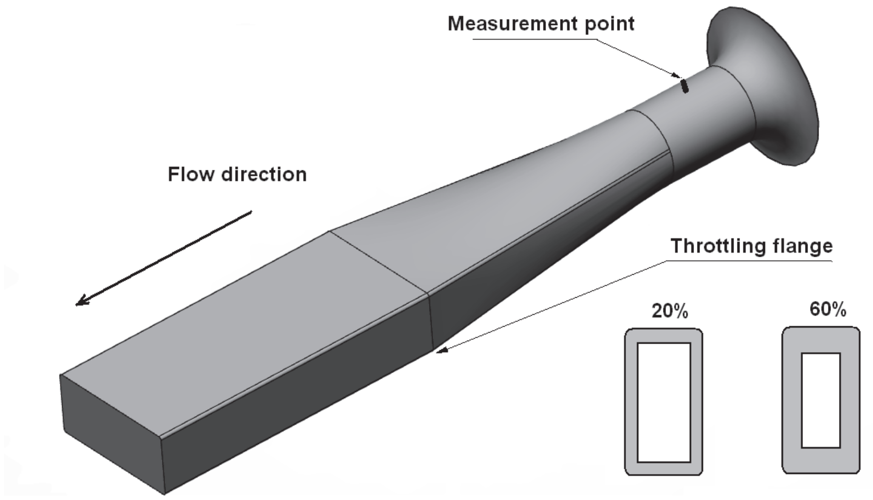

Fig. 1. Scheme of the air intake duct

3. CFD model

According to the ISO standard regulations [5], the quantity of air flow through the Venturi orifice depends on the cross section area of the orifice, pressure differences between the measurement point before the orifice and the point in the orifice, the orifice geometric diametersand the orifice module according to the following dependence:

$$q = \frac{\pi \cdot d^2 \cdot C}{4\sqrt{1-\left(\frac{d}{D}\right)^4}}\sqrt{2\rho(p_1 - p_2)}, \tag{1}$$

where:
q – the mass flow in [kg/s],
d – the diameter of the orifice in [m],
D – the diameter before orifice in [m],
ρ – the density of air in [kg/m^3],
p_1 – the pressure at "D" point in [Pa],
p_2 – the pressure at "d" point in [Pa],
C – the orifice module.

The Venturi orifice module is a function of the geometric dimensions of the orifice, the surface roughness and the Reynolds number of the fluid flow. The simplest method of the orifice calibration is measurement of the flow quantity in the calibration unit. Unfortunately this method is not available in presented case. The reason for this is the necessity of dismantling of the air duct throttling and possibility of changing the orifice module by changing the throttling flange.

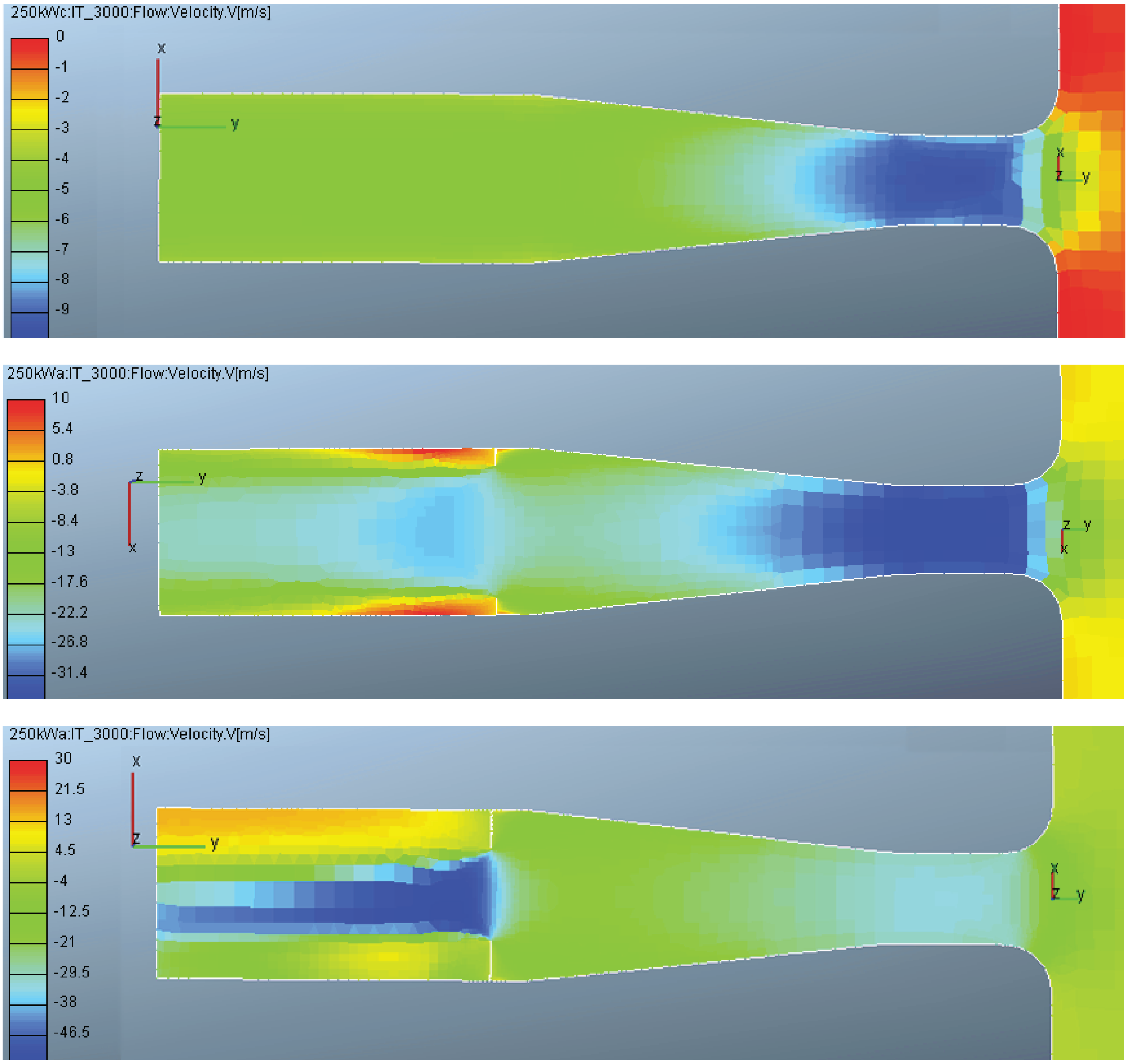

Fig. 2. Velocity in the air intake duct for 250kW the engine load

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

The used software to CFD conduction was AVL Fire. The air intake 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 inlet and the throttling flange area were re-meshed to the minimum dimension equal 1mm.

The momentum and the continuity equations with k-zet-f model of turbulence [2, 8] were performed. The energy balance equations, the heat transfer phenomena and the gravity forces were neglected.

The boundary conditions were selected as follows:

- the air intake duct inlet with the ambient temperature and the ambient pressure,
- the minimal dimension of the Venturi orifice with measured pressure and the ambient temperature.

The maximum number of iterations was set on 3000 and the convergence criteria of the normalized residuals were set. The calculated results, as an extrapolate values of the cross section area of the air intake duct outlet, are volumetric flow of the air, the absolute pressure and the velocity in the axis directionof the air intake duct.

4. Results and discussion

Prepared calculations and laboratory research allows to calibrate the Venturi orifice by the selection of the orifice module. The mean value of mentioned parameter for configuration presented in Fig.1 is 0.792 and the differences between all calculations not exceeded the 6%.

Figure 3 presents all laboratory and calculation results of mass flow through the air intake duct.

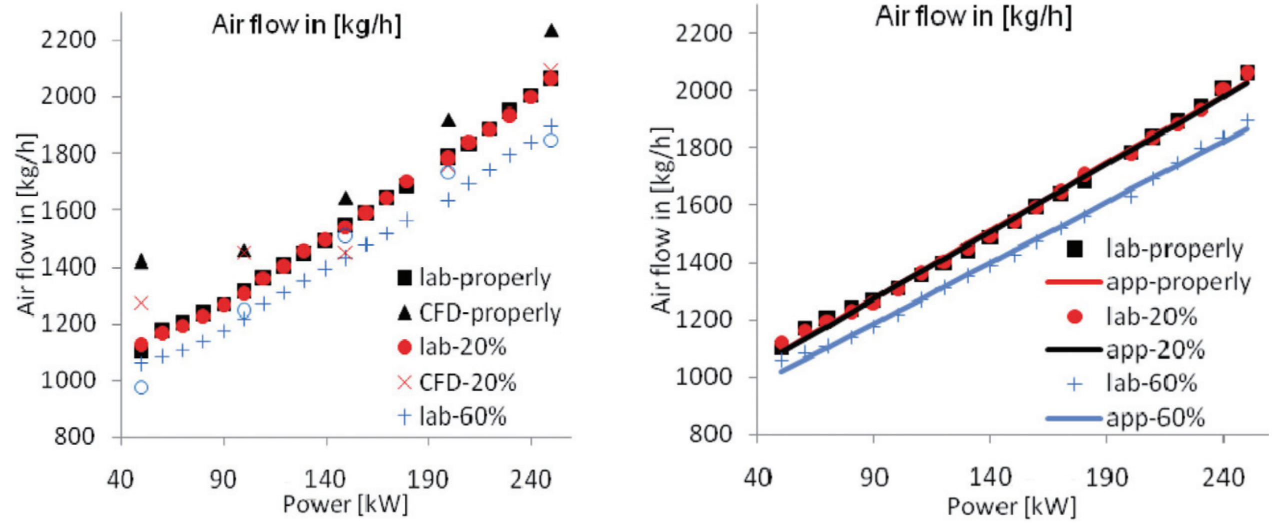

Fig.3. Mass flow through the air intake duct; laboratory, CFD calculation and approximation results

According to presented results only 60% throttling of the cross section area of the air intake duct causes significant decrease of the air mass flow. The results of the air velocity calculations, presented on Fig. 2 may be helpful to explain these phenomena. Fig. 2 presents the example results of the air velocity in axis direction for all laboratory throttling's and engine load equal 250 kW. The air flow through not throttled air duct is laminar and the maximum velocity is in Venturi orifice. The 20% throttling causes some back flows after throttling flanges but the air velocity is still stable and the maximum value is in the orifice. The 60% of throttling causes significant turbulences after the throttling flange. The highest velocity of the air is after mentioned flange and the back flow riches 30m/s. It means that the limitation of the air flow is caused by the turbulence phenomena and the back flows.Results of calculation, presented in Fig. 3, shows the largest differences to the measurement results for a small the engine loads. The reason of this is inaccurate measurement, caused by low differences between the measured static pressures of the air in the orifice. It should be noted that the roughness of the orifice surfaces are not assumed in the CFD calculations.

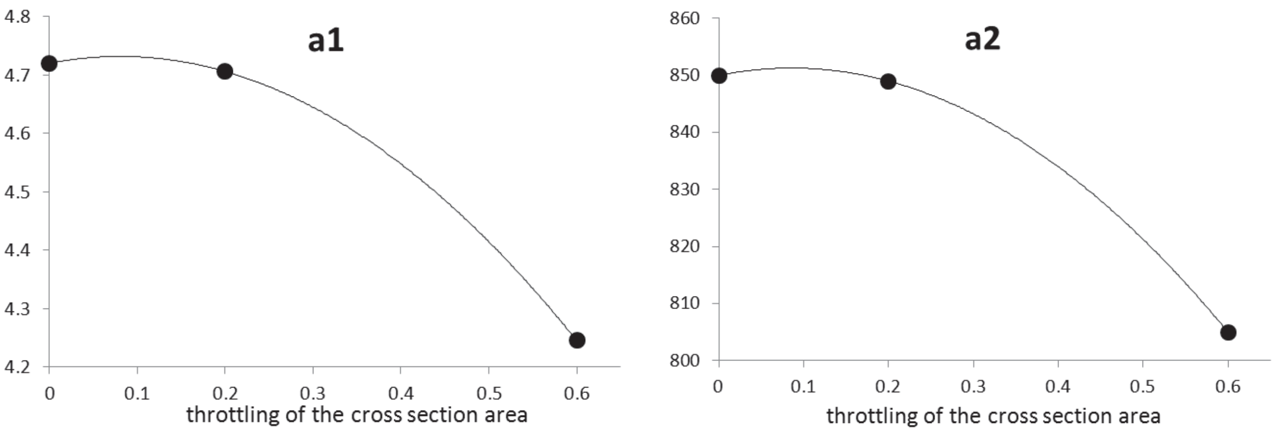

Fig.4. Approximation coefficients for air intake duct flow

The second goal of this research was approximation of the mass flow through the air intake duct in accordance to different throttling's of the air intake duct. Mentioned approximation may be useful tool to modelling the combustion processes in the engine cylinders in the different conditions.

Figure 3 presents the linear dependence between the air mass flow and the power of the engine in the constant engine speed. Mentioned linear approximation is obtained on the basis of the mean square approximation methodology [9]. According to this the approximation of this dependence is the linear function as follows:

$$q = a1 \cdot P + a2\,, \tag{2}$$

where:
q – the mass flow in [kg/s],
P – the power of the engine in [kW],
$a1$, $a2$ – coefficients of the linear function.

The throttling of the cross section area of the air intake duct causes changing the values of the mentioned coefficients "$a1$" and "$a2$". Fig. 4 presents the changes of the coefficients values in function of the throttling value. The black dots presented the measured points. According to presented results the values of both "$a1$" and "$a2$" coefficients may to be approximated by a second order polynomial, according to the following formulas:

$$a1 = b1 \cdot (Th)^2 + b2 \cdot (Th) + b3\,, \tag{3}$$

$$a2 = b4 \cdot (Th)^2 + b5 \cdot (Th) + b6\,, \tag{4}$$

where:
Th – the cross section area of the air intake duct throttling [–],
$b1$–$b6$ – the coefficients of the second order polynomials [–].

It's well known, that is possible to obtain exactly one the second order polynomial from three research points. It should be noted that at the current stage of research, the author found no evidence to conclude that the measurements carried out for other values of the air intake duct throttling would cause a significant deviation from the obtained function. This is confirmed by the CFD calculations.

Presented analyse allows to select the values of "$b1$" to "$b6$" coefficients for the considered laboratory stand. Mentioned values are presented in Tab. 2.The results of calculation the "$a1$" and "$a2$" 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	$b1$	$b2$	$b3$	$b4$	$b5$	$b6$
Value [-]	–1.8	0.29	4.72	–175	30	850

Presented results allow calculating the quantity of the mass air flow for different values of the air intake duct throttling in the range from the 0 to the 60% of the cross section area without direct measurement. The maximum error of obtained approximation compared to measured values not excided 4% and mean error for all measured loads and throttling's not exceeded 0.12%. The coefficient of determination (R^2) for all considered laboratory results and for obtained approximation function equal 0.996. It means that obtained function is well matched for laboratory results. It should be noted that presented function is suitable only for presented laboratory stand.

5. Conclusions

The main goals of the research were calibration of the used Venturi orifice by selection of the orifice module and approximation of the direct measure flow results for different throttling's of the air inlet duct. Author carried out direct measurements of the air flow to the 4-stroke diesel engine for the different characteristics of the air intake duct. The Venturi orifice measurement was chosen. The flow characteristic of the orifice was selected by CFD method.The mean value of the obtained orifice module for considered configuration of the air intake duct equal 0.792 and the differences between all calculations not exceeded the 6%.The CFD results show that quantity of air flow high depends on the turbulence phenomena and back flows after throttling flange.

Linear dependence between the air mass flow and the power of the engine at the constant engine speed was observed. Moreover, the throttling of the cross section area of the air intake duct causes changing the characteristic in accordance to a second order polynomial. Presented approximation allows selecting the values of coefficients of chosen formula. Presented results allow calculating the quantity of the mass air flow for different values of the air intake duct throttling in the range from the 0 to the 60% of the cross section area without direct measurement. The maximum error of obtained approximation compared to measured values not excided 4% and mean error for all measured loads and throttling's not exceeded 0.12%. Mentioned approximation may be useful tool to modelling the combustion processes in the engine cylinders in different throttling conditions.

Presented actions allow preparing the algorithm to calibration the measuring orifices and approximation of the obtained results to the different constructions of the engine air intake ducts.

Result of this is considered reduce the cost of research.

Acknowledgments

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