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A Methodology for a New Qualified Numerical Model of a 2-Stroke Diesel Engine Design

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Abstract **– This paper presents a methodology to determine and to formalize all the variables involved in a CFD model of a 2-stroke diesel engine. The formalization includes the establishing of the values domain and the research of relations between the variables. The formalization can be followed by a reduction of the variables and the ranges of values. The methodology concludes on the qualification of the model.**

The methodology has to be used before solving the model. It helps not to forget any variable and to well understand the characteristics of the final model. It also provides the validity domain of the model and the limits of its exploitation. The methodology is applies to the 2-stroke Diesel engines to optimize its design and characterize the aerodynamics inside the combustion chamber.

Keywords – methology; modeling; qualification; scavenging; 2-stroke diesel engine

Nomenclature

<V,a>	Instantiation of the variable V by the value a
f	Pattern function of the product
g	Performance function of the product
$\mathcal{V}, \mathcal{V}_D, \mathcal{V}_O$, $\mathcal{V}_B, \mathcal{V}_T$	Set of variables
$\mathcal{R}$	Set of relations
$\mathcal{D}$	Set of domains of values
H	Pareto optimal hypersurface
T_o	Operator of order theory
∪	Union operator of set

I. Introduction

Automotive internal combustion engines (ICE) have been studied because of anti-pollution standards more and more drastic.

Despite of the decades of use, their efficiency is still low and improvements can be made in terms of design and performances.

We focus our study on the aerodynamics of the combustion chamber during the scavenging process. Scavenging is the process by which the fresh gases come in the combustion chamber, pushing through the exhaust ports the burnings gases. It plays an important role in the performance and efficiency of engines. The aim of our study is to design the combustion chamber in order to optimize this process.

In order to match the requirements, we have to redesign the cylinder. Due to the difficulties of measurements in the chamber, we rely on a CFD (Computational Fluids Dynamics) model and detailed results. To ensure the quality of the models, we use the following modeling method:

- Characterization of the variables (definitions, ranges of values and relations),
- Reduction of the model,
- Qualification of the model.

II. 2-Stroke Diesel Engine

We study ports for the intake and the exhaust of the gases, so we focus our researches on 2-stroke diesel engines. All details about 2-stroke diesel engine are presented by Blair [1].

From the beginning, two-stroke engines have suffered from high emission and poor fuel economy compared to more efficient 4-stroke engines. But, automotive industry has recently a renewed interest for 2-stroke engines thanks to its advantages. Smaller and lighter than 4-stroke, 2-strokes fire once every revolution offering higher power, greater and smoother torque (Mattarelli [2], Trescher [3]). The main difficulties with the 2-strokes scavenging process by ports are the mixed of burnt and unburnt gases, the short-cutting of the fresh charge as Lamas [4] presented and the backflow of the burnt gases in the intake ducts as Mattarelli [2] underlines.

On the studied engine, there are 3 intake ports on each side of the cylinder: intake port 1 is divided in two different ports separated by a 3mm wall. The separation is required to limit the rings distortion when the rings uncovered the ports. But, in

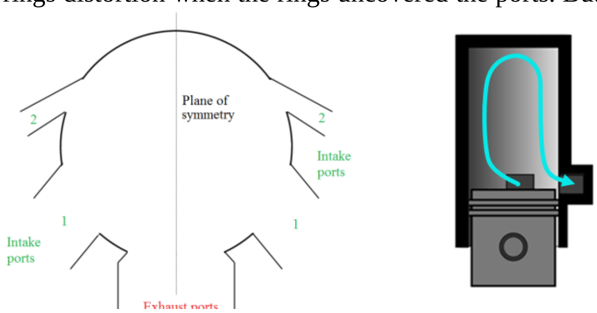

Figure 1 - Top view (left) and side view (right) of the cylinder

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numerical model, the 3mm wall does not impact the results unless a fine mesh is used there. So we chose to simplify the geometry. We set the number of inlet ports to 4 and the number of outlet ports to 1 (see Figure 1).

This configuration is suitable for Schnürle scavenging process as drawn on the side view of Figure 1.

The study is only about the scavenging. The combustion process is complex to model so it will be modeled by classical and simplified combustion law (the heat release Wiebe law, expressed by Ghojel [5]). We assume that the scavenging process occurs far enough after the beginning of the combustion: the combustion is considered as total and over. To set up the pressure and temperature conditions in the cylinder, we use a Matlab® program.

III. Model structure

A model is used to capture in a finite amount of parameters the way (or, at least, a part of) the world reacts. For us, a model is based on a set of:

- Variables, $\mathcal{V} = \{V_1, V_2,\ldots,V_n\}$
- Domain of values, $\mathcal{D} = \{D_1, D_2,\ldots,D_m\}$, $m \leq n$
- Relation(s) between variables, $\mathcal{R} = \{R_1,\ldots,R_p\}$.

with $(n, m, p) \in \mathbb{N}^3$

A. The identification of variables

Definition: a variable is a quantity characterizing a part of the design problem. It is represented by a symbol. The variables making a model can be split in four groups:

- The design variables $\mathcal{V}_D$'
- The objective (or quality) variables $\mathcal{V}_O$'
- The behavioral/environmental variables $\mathcal{V}_B$'
- The technical variables $\mathcal{V}_T$.

$\mathcal{V} = \mathcal{V}_D \cup \mathcal{V}_O \cup \mathcal{V}_B \cup \mathcal{V}_T$.

1) The design variable

Definition: The set of design variables are an influence on the general architecture of the designed model.

f is the pattern function of the product, f described the product in a global or local design way.

$$\forall(a,b) \in D_i^2, \quad V_i \in \mathcal{V}_D \Leftrightarrow f(<V_i,a>) \neq f(<V_i,b>) \qquad (1)$$

Indeed, the design variables enable to distinguish two different designs of the product. The method used to identify the design variables is based on the technical chart (see Figure 2).

2) The quality or objective variables

Definition: the objective variables qualify the ideal state of the product. These variables enable to compare the products in order to determine the best design. All the objective variables must be measurable (qualitatively or quantitatively).

g is the performance function of the product. H is the pareto optimal hypersurface, H=min(g) or H=max(g) depending on the studied case.

$$\forall a \in D_i, \quad V_i \in \mathcal{V}_O \Leftrightarrow g(<V_i,a>) \in H \qquad (2)$$

3) The behavioral or environmental variables

Definition: the environmental variables characterize the environment where the product is used.

$$\forall(a,b) \in D_i^2, \quad V_i \in V_B \Leftrightarrow \begin{cases} f(<V_i,a>) = f(<V_i,b>) \\ g(<V_i,a>) \neq g(<V_i,b>) \end{cases} \qquad (3)$$

The environmental variables do not directly define the system itself. They characterize the influence of the system on the environment or vice-versa.

4) The technical variables

Definition: The technical variables restrain the design because of technical and technological limits.

$$V_i \in \mathcal{V}_T \Leftrightarrow \exists a_i \in \mathbb{R}^i, V_n \in (\mathcal{V}_D \cup \mathcal{V}_O)^n \text{ such as } V_i = T_o(a_i, V_n) \qquad (4)$$

This kind of variables is totally based on the experiences and the know-how of the experts. They are most of time inherent in the experts' mind.

5) Formalization of the variables

To summarize, each variable is characterized by: a name, a symbol, a value, a unit of measurement, a range of values, relation(s) with others variables (see Table 1).

B. The range of value

The range of values provides the maximum and the minimum values the variable can take and the value varies between these two extremes. The range of values can be:

- Continuous, the variable can take any values between the two extremes; the domain is infinite;
- Discrete, the variable can take a finite number of values between the two extremes;
- Mixed, the domain is union of continuous and discrete value domains.

Whatever the range of values is, it can be useful to apply on it a membership function. This function underlines the values to give priority.

C. Relation between the variables

The relations between the variables come from physics, the assembly of the subcomponents… In numerical models, the relations are given by the software itself and the user's inputs (choice of turbulent model, use of the ideal gas law,…).

$$\exists a_n \in \mathbb{R}^n, V_n \in (\mathcal{V}_D \cup \mathcal{V}_O)^n \text{ such as } R_i(a_1 V_1, \ldots, a_n V_n) = 0 \qquad (5)$$

IV. The qualification of the simulation

To qualify our models, we use as basis the 'PEPS' method presented by Ordaz-Hernandez [11] more the time:

- Parsimony $P \in \mathbb{N}$

The parsimony is linked to the number of variable or DOF being involved in a model.

- Accuracy $A \in [0\,;1]$

The accuracy is the difference between the results of the model and the referent case.

- Precision $Pr \in [0\,;1]$

The precision is linked to the way we solve the model and the algorithms of iterative calculations.

- Specialization S,

The specialization described the area of application of the model.

- Time T

The time is linked to the whole time needed to solve the model and the time step needed (time is especially crucial for models which are time and resources consuming).

V. Application to the 2 Stroke Diesel engine

In this paper, we use a discrete numerical model to represent the scavenging process in the engine. But before building this model, it is necessary to determine all the variables involved in the process we want to represent.

To simplify the understanding of each variable and its symbol, we use 'in' as subscript for the intake ports and 'exh' for the exhaust port. We also add the number of the port in order to differentiate the two intake ports (for the numbers, see Figure 1).

The influence of some variables has been already studied by others authors. Because of the engine complexity, we prefer to carry out a multi-parameters study. The most influent parameters on the scavenging process are presented after the technical chart (Figure 2).

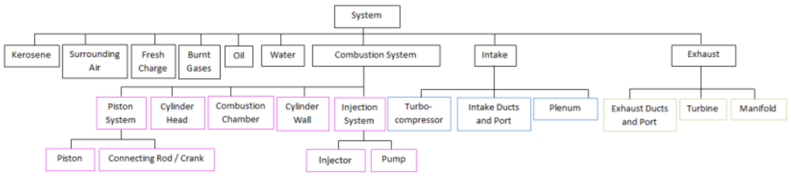

Figure 2 – Technical chart of the combustion engine and its environment

A. *The design variable and range of values*

The angle α is the tangential angle between the port and the cylinder (see Figure 3). α impacts the permeability of the port and the aerodynamics in the chamber (swirl motion - Litke [6], Kato [7], Ingvoversen [8]). An angle α is associated to each ports.

The angle β is the angle between the piston plane at BDC (Bottom Dead Center) and the port (see Figure 3). β is used to limit the dead zones (zones where burnt gases stay, no fresh charges goes there). It also defines the path of the fresh and burnt gases (Maekawa [9]).

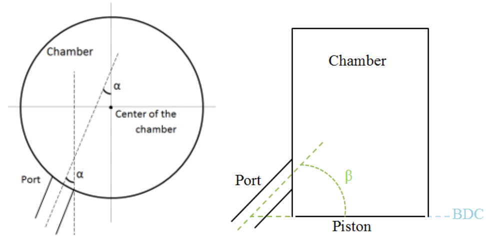

Figure 3 – Angles α and β

α_{in_1} varies from 10° to 40° and β_{in_1} from 0° to 60°. The two inlet ports number 1 converge to a point located between the center and the bottom of the chamber. Thus, the 'Schnürle' scavenging process (see Figure 1) is well initialized. The range of values of α_{in_2} is [70;90]° and β_{in_2} is [0;15]°. Indeed, the inlet ports number 2 are used to limit the dead zone in the bottom of the chamber. α_{exh} is set to provide a good shape to the Schnürle loop end. It varies between 5° and 20° and β_{exh} between 0° and 30°.

The height of the exhaust port $\theta_{end\_exh\_port}$: in opposition of the intake ports, the exhaust port can be fully uncovered before the piston reaches the BDC. The height of the exhaust port can be express as a length. But, we prefer to use the crankshaft angle at which the port is fully opened (the crankshaft angle is a common unit in the engine field). $\theta_{end\_exh\_port}$ will vary from 0 crank angle to 30 crank angle, just enough to determine if the end of the exhaust port has an influence.

The width of the ports w_{in_1}, w_{in_2} and w_{exh}: The permeability of a port depends on its width. Less gas goes through a narrow port than through a wider one. But the width of a port is constrained by technical variables: the mechanical efficiency of piston rings and the openness rate of the cylinder (see below). The choice of width values has to match the technical variables requirements.

The advance of intake opening $\theta_{in\_advance}$: The intake opening advance is the crankshaft angle at which the piston begins to uncover the port. The angle is determined from the BDC. This angle determines both the scavenging process and the compression/power durations. It impacts the quality of the combustion and the quantity of work delivered to the crankshaft. All intake ports have the same open angle.

The advance of exhaust opening $\theta_{exh\_advance}$: As the advance of intake opening, this angle is the crankshaft angle at which the piston begins to uncover the exhaust port.

The opening angles $\theta_{in\_advance}$ and $\theta_{exh\_advance}$ are chosen to allow both the longest expansion and the most efficient scavenging. Moreover, in 2-stroke engines, the exhaust ports are always the first opened and the last closed. It avoids backflow of burnt gases through intake ports because of a higher pressure in the chamber. So, the range of values used for intake and exhaust advances are respectively [35;55]° crank angle and [65;80]° crank angle.

All design variables are formalized in the Table 1.

Name	Symbol	Range of value
Angle α	α_{in_1}	[10 ; 40]°
	α_{in_2}	[70 ; 90]°
	α_{exh}	[5 ; 20]°
Angle β	β_{in_1}	[0 ; 60]°
	β_{in_2}	[0 ; 15]°
	β_{exh}	[0 ; 30]°
Height of the exhaust port	$\theta_{end\_exh\_port}$	[0 ; 30]°crank angle
Width of the ports	w_{in_1}	
	w_{in_2}	
	w_{exh}	
Advance of intake opening	$\theta_{in\_advance}$	[35 ; 55] °crank angle
Advance of exhaust opening	$\theta_{exh\_advance}$	[65 ; 80] °crank angle

Table 1 – Design variables

B. *The environmental variables and range of values*

The boost pressure P_{boost}: It is the pressure of the intake fresh charge. It impacts the quantity of fresh gases entering in the chamber, and the maximum pressure in the chamber during the combustion (Mattarelli [2]).

The range of values of P_{boost} is [1.5;4]bar. This corresponds to the possible pressures considered during the life cycle of the engine.

The difference between intake and exhaust pressures ΔP: The exhaust back pressure is due to the turbine. Rather to talk about 'exhaust back pressure', we prefer to use the difference between the boost pressure and the exhaust back pressure. We consider the difference varies from 0.2 to 0.6.

The intake temperature T_{in}: for same volume and same gas, the coldest gas would have a mass more important than the hottest one. Thus, we cool the fresh charge in order to maximize the mass of gas entering the chamber. We set the variation of intake temperature between 40-80°C.

The engine speed V_{engine}: The engine speed determines the duration in seconds of the scavenging. The higher is the engine speed, the shorter is the duration (Mattarelli [2]). During it use, the engine will turn between 2000rpm and 3000rpm. The engine idle is not taken into account.

All behavior variables are formalized in the Table 2.

Name	Symbol	Range of value
Boost pressure	P_{boost}	[1.5 ; 4]bar
Intake and exhaust pressures difference	ΔP	[0.2 ; 0.6]bar
Intake temperature	T_{in}	[40 ; 80]°C
Engine speed	V_{engine}	[2000 ; 3000]rpm

Table 2 – Environmental variables

C. *The technical variables and range of values*

The openness rate of the combustion chamber represents the percentage of opened width comparing with the total width. This rate ensures that, wherever we are in the cylinder, the openness does not exceed 70% of the total chamber perimeter. Over 70%, the experts cannot guaranty the mechanical efficiency of the materials because of the high pressure and temperature.

The total intake ports surface area and the total exhaust port one are connected together. It is easier to evacuate the burnt gases than to enter the fresh charge. That is why the total intake surface area is always bigger than the total exhaust one.

The width of the ports is limited. The tightness of the chamber is made by the piston metal rings. When the piston uncovers the ports, the rings are distorted and partly take the port form. The larger is the port, the bigger is the distortion of the ring. After several cycles, this distortion can affect the rings ability to seal.

D. *The objective variables*

To compare the scavenging efficiency in different chamber design, we use 4 main parameters (Heywood [10]):

- The delivery ratio $\Lambda = \dfrac{mass\ of\ deliverd\ air\ per\ cycle}{reference\ mass}$ (6)
- The trapping efficiency $\eta_{tr} = \dfrac{mass\ of\ deliverd\ air\ retained}{mass\ of\ delivered\ air}$ (7)
- The scavenging efficiency $\eta_{sc} = \dfrac{mass\ of\ deliverd\ air\ retained}{mass\ of\ trapped\ cylinder\ charge}$ (8)
- The charging efficiency $\eta_{ch} = \dfrac{mass\ of\ deliverd\ air\ retained}{displaced\ volume\ \times\ ambient\ density}$ (9)

The trapping and charging efficiencies are linked to the delivery ratio by the equation 5: $\eta_{sc} = \Lambda \times \eta_{tr}$ (10)

VI. A 2D Stroke Diesel engine model

A. *Discrete numerical model*

Except for the variables, we use the same hypothesis and parameters for all numerical models. The first hypothesis we use is all cylinders in the engine are identical so we solve the model of only one cylinder. The second hypothesis is about the combustion process which is not simulated (see II) but characterized by a heat release law, independently of the model.

The governing equations were solved using the commercial software Ansys® Fluent® 14.5, based on the finite volume method. The computer used to run the model is a Core i7, 2.40 GHz with 8Go of RAM.

Governing equations	RANS (Reynolds-Averaged Navier-Stokes) equations
Thermal exchanges	Energy equation
Material mixtures	Mass fraction field equation
Turbulence model	k-ε realizable model (Lamas [12])

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Wall treatment	Enhanced wall treatment
Spatial discretization	Second order scheme
Temporal discretization	First order implicit discretization

B. *Qualification*

Accuracy

Our reference frame is a cylinder built by a 3D printer. We do not fire the prototype. The piston is placed in the chamber by hand and it is fixed during the experiment. We did experiments for several positions of the piston in a wind tunnel which calculates the mass flow rate and the effective surface.

Figure 4 – Wind channel and experimental chamber

We position the piston in two different places: at the BDC and in order to cover half intake ports. We only compare 3D numerical and experimental results of the mass flow rate.

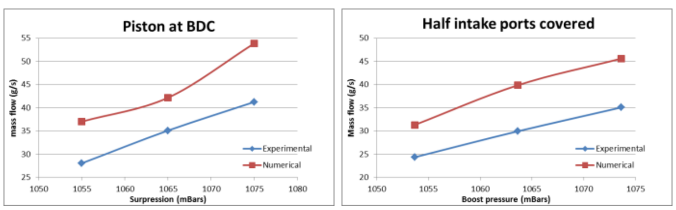


Figure 5 – Accuracy results

There is always a difference of about 20% between the numerical and experimental results; it comes from several issues like the numerical approximation and the default of experimentation (a leak was found and will be measured later).

Precision

The size of the mesh impacts the precision of the results. We studied the influence of different mesh sizes on the results. The piston is at BDC. The intake and exhaust pressures are respectively 1.2bar and 1bar. The intake and exhaust temperatures are respectively 60°C and 25°C. The intake and exhaust mass flow rates, the averaged pressure and the averaged turbulent energy (both in the cylinder) were compared. The results are below:

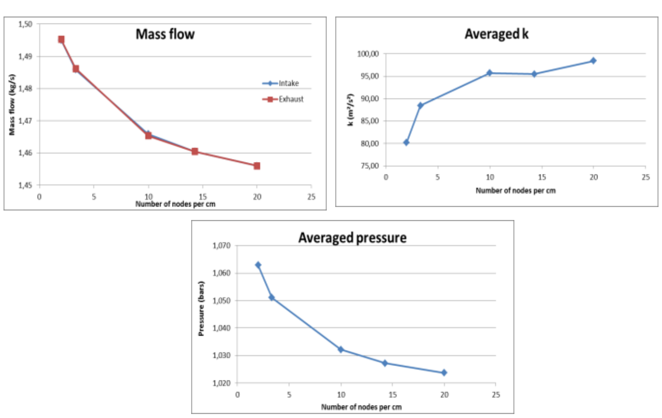


Figure 6 – Precision results

The difference between the results of two consecutive sizes is important until we reach 10elements/cm. The difference significantly reduces between 10elements/cm and lower mesh size. We conclude that the best mesh size should be around 10 elements per centimeter.

Time stepping

The time step has to be chosen very carefully, finding the best compromise between convergence and duration. We studied the influence of different time steps on the scavenging model. To limit the duration of calculations, we tested a 2D model. We consider that, concerning the time step, the 2D results can be applied to the 3D model.

We used the same boundary conditions for all models:

- V_{engine} = 2500 rpm
- P_{in} = 1.7 bar
- P_{exh} = 1.1 bar
- T_{in} = 60°C (333.15K)
- T_{exh} = 600°C (873.15K)

The initial conditions in the cylinder are 750°C and 7bars.

The simulation starts at 100 crank angle after TDC (Top Dead Center), the exhaust port opens at 101 crank angle and the intake one at 106 crank angle. The total duration is 9 crank angles. At the beginning, the mesh counts 34,623 nodes.

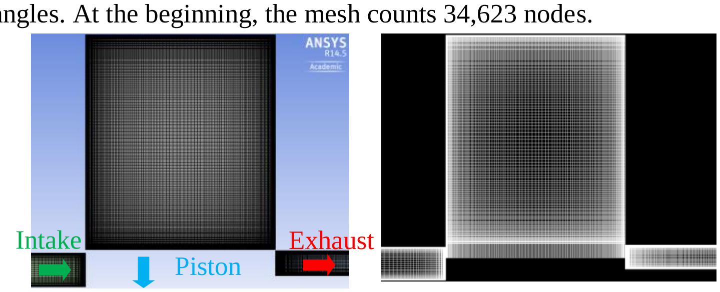


Figure 7 – Mesh at the beginning and at the end of the simulation

The first result we get is the results diverge if the time step exceeds 3E-6s (equivalent to 0.045 crank angle). We used three tests of time steps (see Table 3).

	Time step	Number of iterations	Equivalent crank angle
Test 1	1E-6s	600	0.015
Test 2	2E-6s	300	0.03
Test 3	3E-6s	200	0.045

Table 3

We compared the average pressure, temperature and turbulent energy in the chamber and the intake and exhaust mass flow rate. We take as reference the results of Test1 (with the smallest time step). We obtained the results in Table 4:

Crank Degree	Time Step	P (Bars)	T (K)	k (m²/s²)	Inlet mass flow (kg/s)	Outlet mass flow (kg/s)
109	1,00E-06	5,454	954,27	0,529	3,053	3,780
	2,00E-06	5,450	954,07	0,539	3,056	3,770
	3,00E-06	5,446	953,93	0,553	3,057	3,764

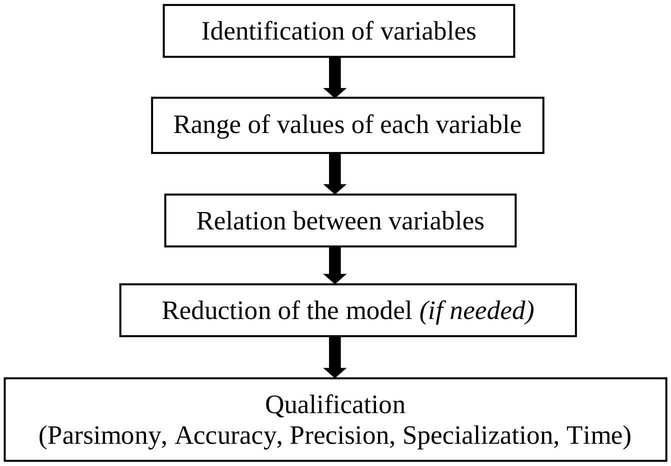
Table 4 – Results

With a smaller time step, we could expect to see local phenomena or to have faster and better convergences. However, there is no major difference in the results when the time step varies. Moreover, the time duration of the simulation was around 20min in Test 3 (whereas we needed 1h to run the Test 1); and the convergences are quite identical in all tests.

The time step will be set to 3E-06s in the next simulations.

VII. Conclusion

The methodology presented is:



This methodology has to be used before solving the model. It helps not to forget any variable and to well understand the characteristics of the final model. The user keeps the control at each step. The methodology also provides the validity domain of the model and the limits of its exploitation.

First of all, we used the methodology to establish the engine model. Applied to the numerical modeling of a 2-stroke Diesel engine, the results we got show the interest of the method. The number of variables we found was too important and required a first stage of reduction before the qualification. Then, we began the qualification of the model. The results in exactitude and time parts are satisfactory and lead us to these conclusions: the most suitable time step is 3E-6s (0.045 crankshaft angle) and the difference between the numerical and experimental results do not exceed 20% which is good enough for us. For the mesh size, 10 elements per centimeter seem to be a good compromise between accuracy and calculating time.

References

[1] Blair GP. "Design and Simulation of two-stroke engines". Engineers, Society of Automotive; p. 641, 1996.

[2] Mattarelli E. "Virtual design of a novel two-stroke high-speed direct-injection diesel engine". Int. J. ENGINE Res. 10(3):175–93, 2009;

[3] Trescher D. "Development of an Efficient 3–D CFD Software to Simulate and Visualize the Scavenging of a Two-Stroke Engine". Arch. Comput. Methods Eng. 15(1):67–111, 2008;

[4] Lamas M. I., Vidal C. G. R. "Computational Fluid Dynamics Analysis of the Scavenging Process in the MAN B&W 7S50MC Two-Stroke Marine Diesel Engine". J. Sh. Res. 56(3):154–61, 2012;

[5] Ghojel J. "Analytical Heat Release Function for DI Diesel Engines". 4th Asian-Pacific Int. Symp. Combust. Energy Util. 1991.

[6] Litke B. "The influence of inlet angles in inlet ports on the scavenging process in two-stroke uniflow-scavenged engine". Mar. Technol. III, Mar. Marit. 1:247–52, 2000;

[7] Kato S, Nakagawa H, Kawahara Y, Adachi T, Nakashima M. "Numerical analysis of the scavenging flow in a two-stroke-cycle gasoline engine". JSME Int. journal. Ser. 2, Fluids Eng. heat Transf. power, Combust. Thermophys. Prop. 34(3):385–90, 1991;

[8] Ingvorsen KM, Meyer KE, Schnipper T, Walther JH, Mayer S. "Swirling Flow In Model Of Large Two Stroke Diesel Engine". 16th Int. Symp. Appl. Laser Tech. to Fluid Mech. 2012;

[9] Maekawa M. "Text of Course". JSME G36. (23)1957;

[10] Heywood JB. "Internal Combustion Engines Fundamentals". McGRAW-Hil. Duffy A, Moms JM, editors. p. 930, 1988.

[11] Ordaz-Hernandez K, Fischer X, Bennis F. "A Mathematical Representation for Mechanical Model Assessment: Numerical Model Qualification Method". Int. J. Math. Sci. 1(4):216–26, 2007;

[12] Lamas MI, Rodríguez CG, Rebollido J. "Numerical model to study the valve overlap period in the Wärtsilä 6L46 Four-stroke marine engine". Polish Marit. Res. 19:31–7, 2012;

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