Numerical modelling of engine operation with a variable state of compression

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Abstract
The paper presents the modelling the engine operation with a variable state of compression with the use of the Reverse Engineering method and simulations of the phenomena with the use of the Ansys Fluent software package. The analysis and selection of appropriate combustion parameters directly affects the degree of fuel consumption in petrol engines. Less fuel consumption means not only lower operating costs but also less environmental pollution.

Keywords
Reverse engineering, Computational fluid dynamics CFD, Variable compression ratio VCR

1. Introduction

Bearing in mind the current need to care for the natural environment [1], one of the important factors is the emission of exhaust gases. By reducing fuel consumption in internal combustion engines while maintaining torque, operating costs and the amount of pollutants emitted are significantly reduced. One of possible solutions is the employment of variable compressions ratio. Due to occurrence of engine knocking at higher engine speeds, modern internal combustion engines have a compression ratio of approximately 10:1. Use of a higher compression ratio (as much as 15:1) would be more beneficial in the aspect of fuel consumption. Because higher compression ratios are dangerous to the engine, especially at higher engine speeds, the concept of regulating the compression ratio depending on engine speed appears rational.

The efficiency of an internal combustion engine operating according to Otto's theoretical cycle is given by the formula:

$$\eta_t = 1 - \frac{1}{\varepsilon^{k-1}} \tag{1}$$

where ...

η_t – theoretical efficiency,
ε – compression ratio,
k – polytropic exponent.

Equation (1) shows that increasing the compression ratio of the engine will increase its efficiency. Increasing the efficiency of the engine will reduce fuel consumption with the same dynamic parameters of the engine or increase power and torque for the same amount of fuel supplied to the engine. Hence, for many years, work has been carried out on constructions enabling dynamic change of the compression ratio depending on the engine speed [2].

One of the solutions is the design of the SVC (Saab Variable Compression) engine [3]. It uses a variable angle of inclination of the motor head. Tilting the head by 4 degrees changes the compression ratio from 14:1 to 8:1. The angle of inclination of the head is smoothly adjustable depending on the

engine speed (Fig.1). For low engine speeds, the head is positioned vertically to the piston axis (Fig.1a). In this position, the minimum volume of the combustion chamber is obtained. At the same time, this results in a maximum compression ratio. As the engine speed increases, the head tilts away from the piston axis (Fig.1b). Deviation of the cylinder head de-symmetrizes the combustion chamber, increasing its volume. Increasing the volume of the combustion chamber while maintaining the same cubic capacity results in lowering the compression ratio. The appropriate mechanism is responsible for the appropriate adjustment of the tilt angle of the head. When tilting the head, the position of the crankshaft remains unchanged


14:1   8:1
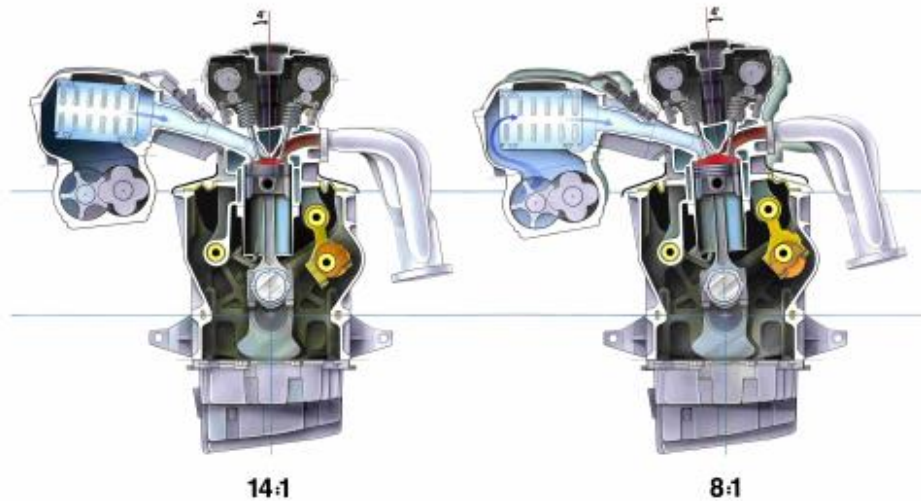
Figure 1: Working principle of variable compression ratio (VCR) in SVC engine [3]
a) maximum compression ratio of 14:1   b) minimum compression ratio of 8:1

A Variable Compression-Turbocharged (VCT) system was developed by a Japanese manufacturer in cooperation with Nissan. This system was tested on a turbo-charged engine with displacement of under 2000 cm3. This system allows for a smooth change in compression ratio in the spectrum ranging from 14:1 to 8:1 [4]. This range is similar to the previously described SVC system. However, in this system compression ratio is adjusted not by regulating the cylinder head, but the piston and connecting rod, as seen in fig. 2 [4]. The base of the connecting rod has been supported by a guide. The guide cooperates with an eccentric, transferring its motion to the base of the connecting rod. This in turn changes the distance of the piston from the rotational center of the crankshaft.
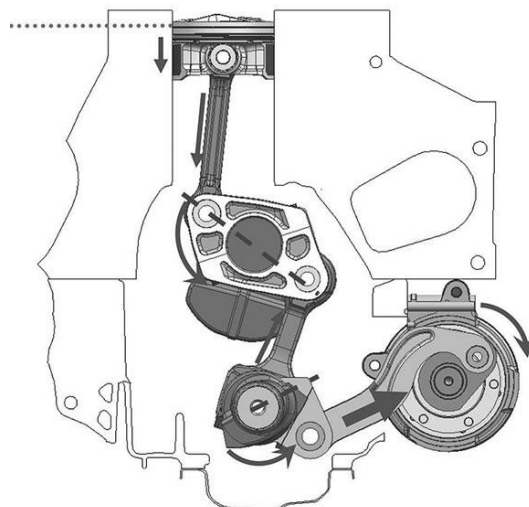

Figure 2: Working principle of variable compression ratio in Nissan VCT engine [2]

A the Faculty of Mechanical Engineering and Aviation of Rzeszów University of Technology, a variable compression ratio engine was constructed on the basis of a conventional 4 VD 14,5/12-1 SRW type engine [5]. Variable compression ratio is achieved by means of movement of the cylinder head, which is integrated with pistons. Position of the cylinder head changes in accordance with the direction of piston movement. This is achieved with the use of a special bolt mechanism shown in figure 3. Movement of the cylinder head is synchronized by a gearbox consisting of sprockets and a transmission belt. Compression ratio is changed continuously and concurrently for all cylinders in the range from 19:1 to 9:1.
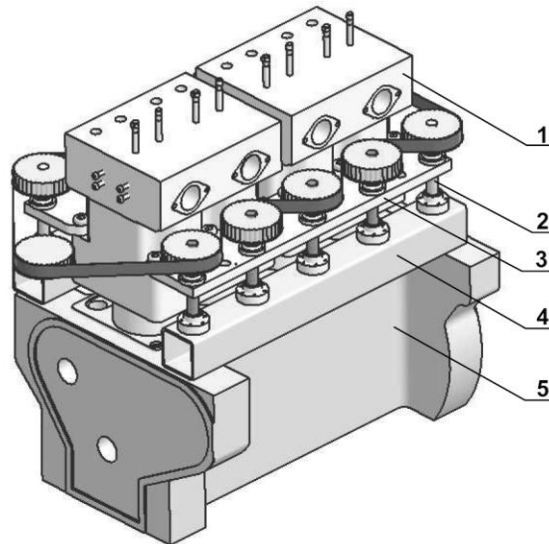
Figure 3: Schematic of the 4 VD 14,5/12-1 SRW VCR engine mechanism [5]:
1 – cylinder head, 2 – synchronized set of bolts, 3 – upper base, 4 – lower base, 5 – engine block.

The presented solutions require significant interference with the construction of the engine. This is a costly solution, as it requires appropriate adaptation of motor production lines. Therefore, in the patent [6], a solution with a wastegate was proposed that minimizes interference with the existing engine design.
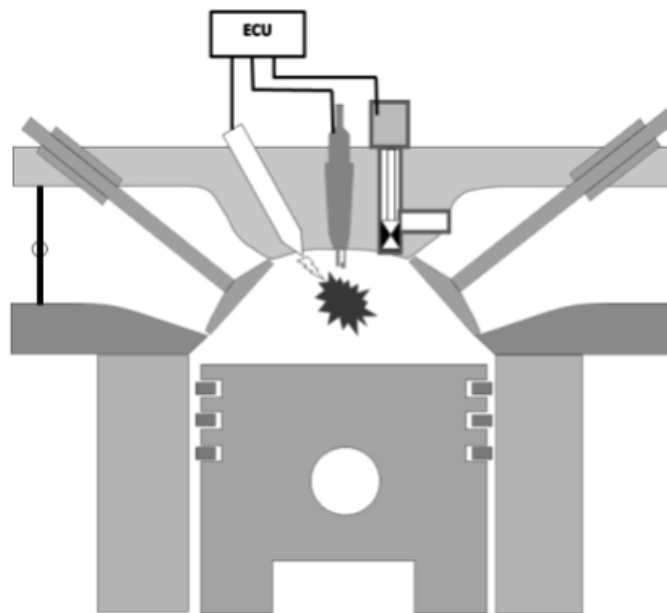
Figure 4: Zasada działania badanego silnika z zaworem upustowym [6].

The subject of this work is the solution described in patent application No. P.414750 of 10-11-2015 [6]. Working principle of the modeled engine is depicted in fig. 4. The main element which controls

and varieties the compression ratio is the blow-off valve placed in the cylinder head. The engine is designed with a higher than typical compression ratio. When the engine is idling, the valve remains closed, allowing to obtain a high effective compression ratio. At higher engine speeds the compression ratio is lowered by means of the valve releasing a certain portion of the air from the combustion chamber. The valve is opened at the initial phase of the compression stroke, directly after piston reaches the bottom dead center. The blow-off valve is operated by an electronic system which cooperates with the ECU and injection control unit.
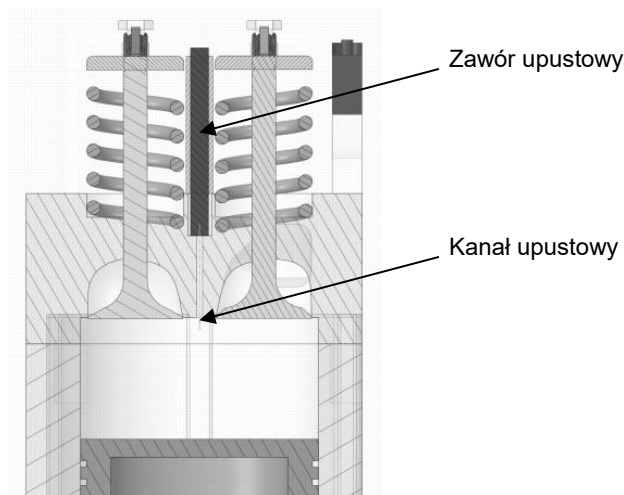
Figure 5: How to install the wastegate valve in the cylinder head.

Figure 5 shows how to assemble the discharge valve. This type of solution only slightly interferes with the construction of the engine. In principle, the existing structure is kept intact, and only a discharge valve should be placed in the head between the valves and an appropriate discharge channel should be drilled in the head (Fig. 5). Since the discharge valve is controlled electronically, it is necessary to design an appropriate control system. This system should, based on the measurement of engine rotational speed, open the discharge valve well in advance, which should be opened for a certain period of time.

2. Badania numeryczne

Due to the need to enter the valve opening times and opening start times into the bypass valve control system, it is necessary to determine the relationship between these times and engine revolutions. For this purpose, a numerical model of the engine operation was developed, with the structure shown in Fig. 4. A computer simulation should allow to verify the proposed design and determine optimum opening and closing angles of the valve. Moreover, the simulation was used to determine critical engine operation parameters. Those critical parameters include engine speed and compression ratio at which engine knock will begin to occur. This data, along with flow parameters of the blow-off valve will allow to properly program the Engine Control Unit. Flow analysis in engines is very important as gas flow affects the efficiency of the engine.

Numerical research was based on an existent geometry of the engine prototype. Ansys FLUENT software with SpaceClaim and ICE (Fluent) modules was used to simulate engine operation. To ensure that simulation data is in best possible agreement with reality, 3D scans of engine components were performed to depict engine geometry as accurately as possible. A finite element mesh was generated basing on obtained 3D scan data.

The paper presents the issues related to the mapping of the shape and generation of the computational mesh. Attention was drawn to the important elements of geometry that cause serious difficulties in generating a computational mesh. The paper discusses ways of introducing appropriate simplifications aimed at accelerating numerical calculations..

3. Computational model

In the first stage, a three-dimensional numerical image of the prototype engine had to be developed. Since the basis for modeling is the existing prototype, it is necessary to reproduce its shape as faithfully as possible so that in the future the results of the numerical analysis could be used to determine the proper parameters of the prototype engine control system. In order to faithfully reproduce the shape of the existing engine elements, the Reverse Engineering method was used. This method consists in 3D scanning of existing elements, and then generating their vector equivalents on this basis..

a)   b)
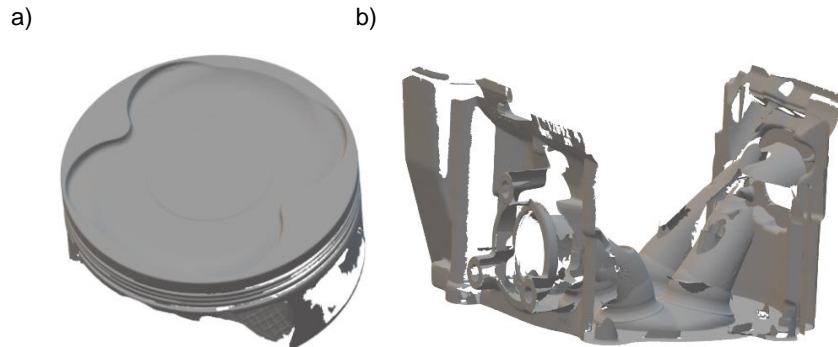
Figure 6: Three-dimensionally scanned engine elements a) piston b) cylinder head.

Three-dimensional representations of main engine parts were obtained through 3D scanning (fig.5). As can be seen, those representations contain many defects, lacking surface continuity. Therefore they required further 3D modeling work to obtain continuous surfaces depicting shapes that are in agreement with real shape of the engine components. Despite this, the use of 3D scanning allows to retain proportions and basic dimensions of scanned elements, facilitating further modeling. Remaining element surfaces were generated with the use of SpaceClaim software, which is part of the Ansys FLUENT package.

### 3.1. Problems with generating surfaces describing engine elements

In order to obtain a three-dimensional image of the basic engine components, the SpaceClaim module was used. This module has tools for processing surface objects (Mesh). This mapping consists in indicating characteristic points and creating a mesh with a given density, which brings the scanned surface (gray) closer to the parameterized surface (green), which allows to create a solid (Fig.7).
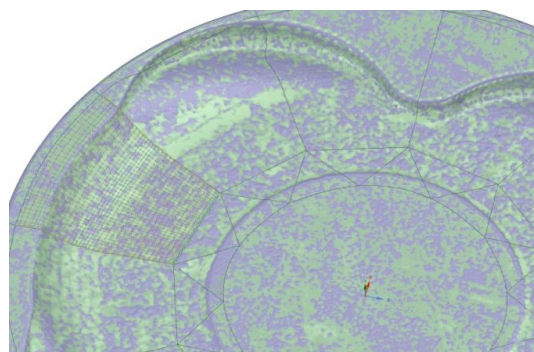
Figure 7: Generation of surface depicting the engine piston basing on 3D scan data

The surface generated by the software recreates the scanned object with accuracy greater than 10 µm. The solid generated in this way is a matrix with several thousand characteristic points, which means that further numerical calculations would require very high computing power. The solid generated in this way is a matrix with several thousand characteristic points, which means that further numerical

calculations would require very high computing power, and it would often be impossible to carry out calculations on such a complex object using the FEM method. Therefore, part geometry has to be simplified in a way that allows to retain details significant for the accuracy of numerical calculations.

a)   b)
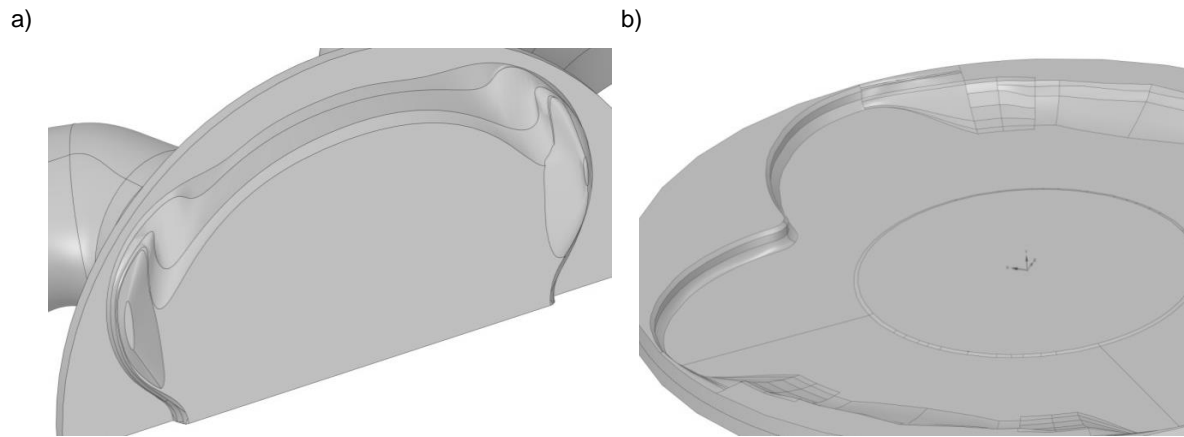
Figure 8: Examples of part geometry simplification by means of   a) extrusion by leading curves
b) joining of simple solids

Figure 8 shows two ways to simplify geometry available in SpaceClaim. A much better mapping is obtained using the method of combining simple solids. Often this type of algorithm is not good enough, because in some places the surfaces generated in this way may lead to incorrect generation of computational meshes for the FEM method. In these areas, it is necessary to enter the surface manually. However, this requires some experience from the operator

In order to verify the correctness of the generated surfaces, the SpaceClaim module has a rich library of validation tools. Using the tools, it is possible to detect unnecessarily divided curves, overlapping solids, find small or missing surfaces. This type of test at the initial design stage will allow for significant time savings in subsequent modeling stages

3.2.   Numerical assumptions

The next stage of modeling works is putting the individual elements into an assembly and giving them specified constraints associated with boundary conditions.

A very helpful tool is the PortFlow module that allows you to quickly verify the correctness of the operations performed. It simulates the calculations without modeling the combustion of the mixture - the calculations are made only for the gas flow. This allows you to quickly check the correctness of the earlier stages, and by radically reducing the modeled phenomena, it significantly shortens the verification process

The Design Modeler module in Ansys FLUENT software was included with this purpose in mind. Working with this module is largely automated, requiring the user to specify units, import geometries and specify characteristic surfaces, solids or points. With the use of Decompose command, the software rebuilds the imported geometry for further use in accordance to prior user specification. The module deletes parts of the geometry, while simplifying or adding others, basing on imposed constraints. Therefore, obtained part geometries can differ from base ones, depending on assumed constraints.
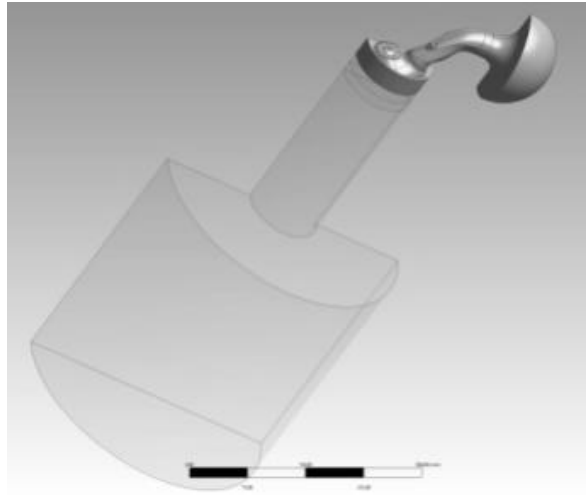
Figure 9: Reshaping the model in DesignModeler software for Port Flow analysis

An example of geometry for Port Flow simulation was depicted in fig 8. In comparison, a piston model intended for more complex "Combustion Simulation" analysis will be rebuilt to a more complex shape, as depicted in fig. 9. At the design stage, it is recommended to check the validity of previously developed geometry by running several different analyses, with the use of "Decompose" command, which checks key parameters of analyzed solids.
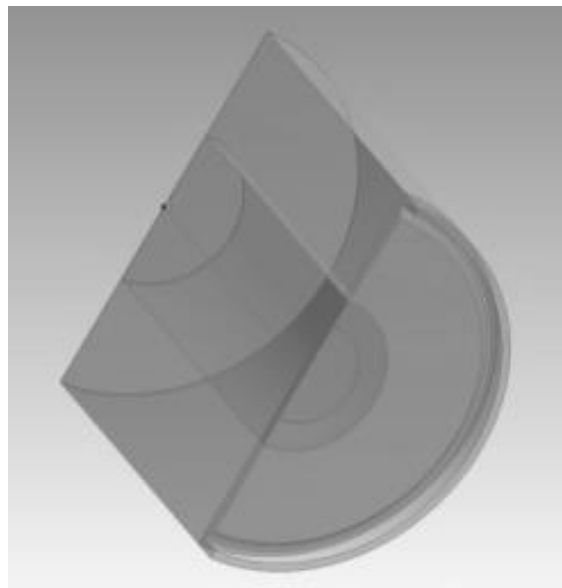
**Figure 10**: Reworking the model in Design Modeler for Combustion Simulation (Sector) analysis

3.3. Generation of finite element mesh

A very important and relatively difficult step is the FEM mesh generation. The Meshing Module in Ansys FLUENT is designed for this purpose. This stage of work is considered difficult, as many geometry errors become evident here. An FEM mesh generated for geometry seen in fig. 8 is depicted in fig. 10. Only at first look the mesh seems correctly generated, however after checking mesh validity with the use of „Orthogonal Quality" and „Skewness" commands, it can be seen that the mesh possessed numerous faults, which generate errors in further computations, making correct analysis impossible.
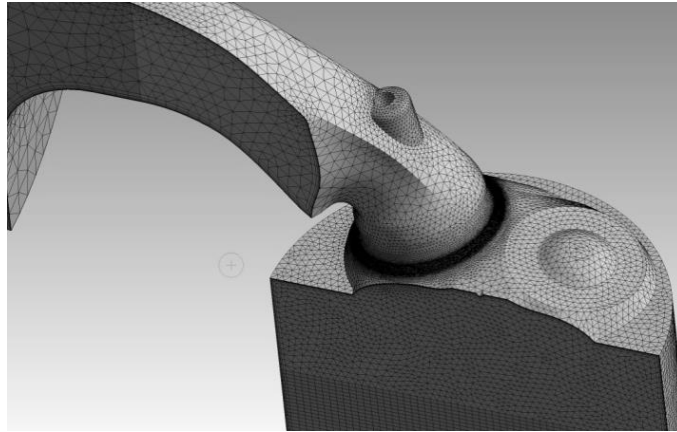
Figure 11: FEM mesh generated in Meshing module

Example of mesh errors are depicted in figure 12. They are mainly associated with the near-surface layer. In analysis of flow phenomena, it is especially difficult to model sharp edges. Leaving these areas in this form will significantly prolong the calculations, and in extreme cases will lead to divergence of numerical calculations or will generate division by zero errors. However, on a macro scale, they do not have a major impact on the nature of the fluid flow. Therefore, it is recommended to round the edges wherever possible.

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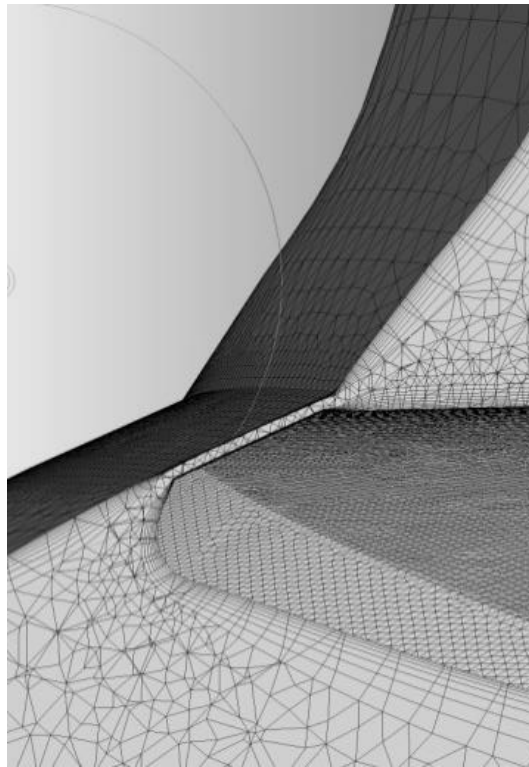
Figure 12: Cross-section of near-surface layer generated by the software at edges of solids

3.4.   Simplifications

Due to the time of calculations, a number of tests were carried out involving the introduction of simplifications of the geometry that do not significantly affect the quality of the numerical simulation. On this basis, it was found that sufficiently good results are obtained for a relatively simple geometry,

while maintaining accuracy in mapping the volume of the combustion chamber, compression ratio, piston diameter, diameters of the intake and exhaust channels. Keeping these criteria is sufficient to achieve the goal of computer simulation, namely to determine the critical operating parameters of the internal combustion engine. To achieve this goal, it was sufficient to simplify the shape of the combustion chamber to the form shown in Figure 13.
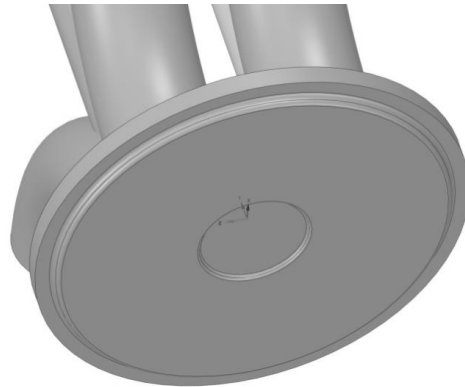
Figure 13: Simplification of combustion chamber and intake port geometry

If more accurate results are obtained, a more accurate mapping of the combustion chamber is necessary (Fig. 14a). This solution results in unnecessary density of the mesh on the sharp curves of the inlet channels. Hence, the simplification consisting in smoothing the arcs of the inlet channels (Fig. 14b) does not cause significant differences in the simulation results, and significantly speeds up the calculations.
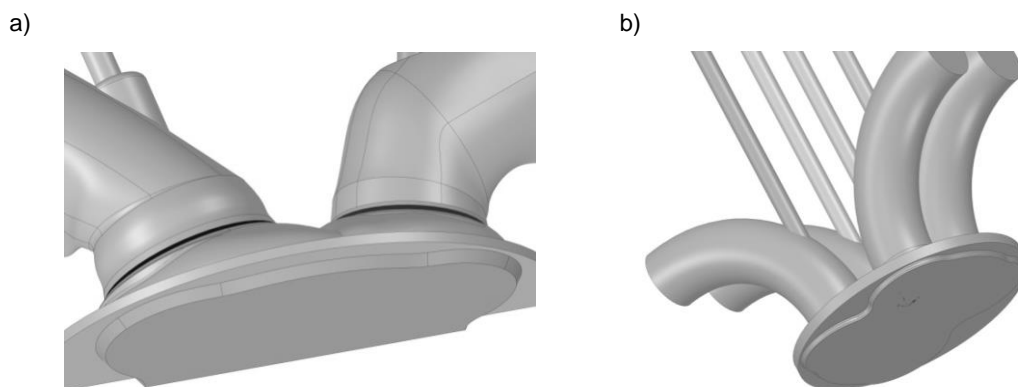

Figure 14: Simplification of intake duct geometry a) simplification of piston surface b) simplification of combustion chamber and intake port geometry along with piston surface optimization

4. Podsumowanie i wyniki badań

The problems of modeling flow problems in internal combustion engines discussed in the paper were used to develop a numerical model of the engine. This model makes it possible to calculate the compression parameters in the engine chamber. On this basis, it is possible to determine the critical parameters of the engine's operation. Figure 15 shows exemplary calculation results. The results were related to the angle of rotation of the crankshaft. Figure 15a shows the cycle of movement of the piston and the intake and discharge valve. Figure 15b shows the maximum values of pressure and temperature in the cylinder for the cycle defined in this way. On this basis, it is possible to analyze changes in parameters inside the engine chamber and determine the times related to controlling the discharge valve so as not to lead to premature ignition in the engine combustion chamber

a)
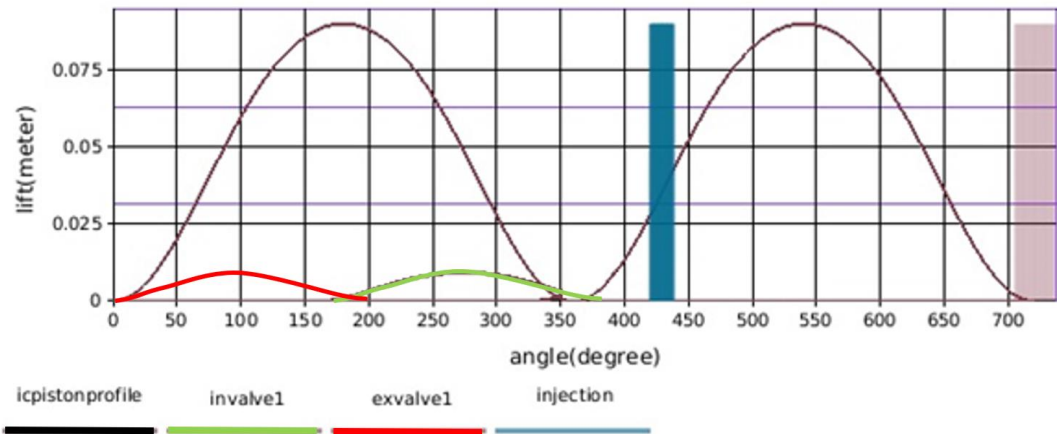
b)
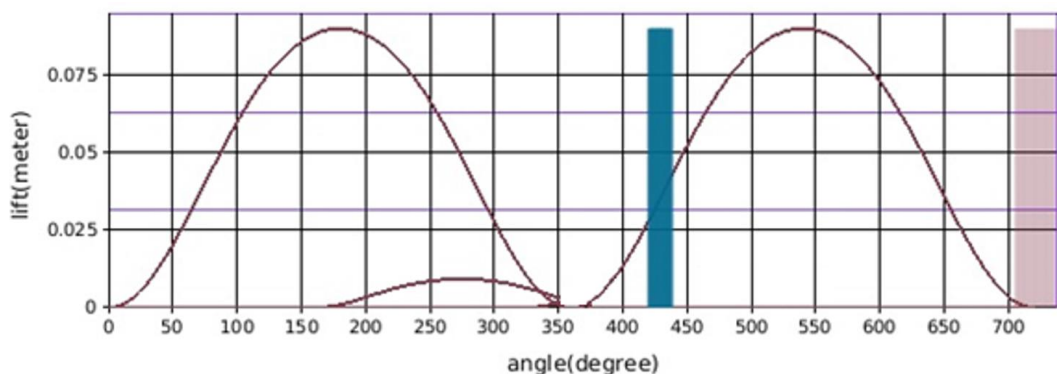
Figure 16: Engine duty cycle simulation results a) set duty cycle parameters b) calculated cylinder pressure

5. Acknowledgements

6. References

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