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Model validation of the SI test engine

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Summary. The results of thermal cycle modelling of spark ignition internal combustion engine are presented. The modelling was carried out in the AVL FIRE. The object of investigation was a S320 spark-ignited internal combustion engine powered by gasoline. The author considered the effort to generate a complete mesh for the test engine, including the intake and exhaust ports and the valves. This involved generation of four computational domains. A local and temporary thickening of the mesh was included, which contributed to more accurate solutions and shortening of computing time, as well as the engine calculations cycle. The numerical analysis results were juxtaposed with the results of indicating the engine on the test stand. The created model of SI engine was successfully verified.
Key words: engine, simulation, modelling, combustion.

INTRODUCTION

Engines are designed to maximize power and economy while minimizing exhaust emissions. This is due to the growing concern with decreasing energy resources and environmental protection. For this reason, intensive research is being carried out and development is in progress on internal combustion engines. The engine should operate with the greatest efficiency with the least toxic compound emissions. Research on improving the combustion process, introducing a new fuel such as hydrogen, and optimization of the engine parameters is still being carried out. Maximizing the performance of the engine (BMEP) usually causes the occurrence of the so-called knock combustion. Therefore, intensive researches and development in internal combustion engines are carried out.

Researches based on numerical simulations using advanced mathematical models have recently been developed very intensively. The development of numerical modelling is heightened by increasing computational power that allows not only the modelling of flow processes but also combustion in 3D [1, 2, 3]. One of more advanced numerical models used for combustion process in internal combustion engines modelling is AVL FIRE [4]. In 2009 the Institute of Internal Combustion Engines and Control Engineering of Czestochowa University of Technology began University Partnership Program with AVL Company. This has allowed the use of the Fire software to IC engine thermal cycle modelling [5, 6, 7]. The AVL FIRE software belongs to programs which are used to modelling of thermal cycle of internal combustion engines. FIRE allows the modelling of flows and thermal processes occuring in the intake and exhaust manifold and in combustion chamber of internal combustion engine. This program allows for the modelling of transport phenomena, mixing, ignition and turbulent combustion in internal combustion engine. Homogeneous and inhomogeneous combustion mixtures in spark ignition and compression ignition engine can be modelled using this software, as well. Kinetics of chemical reactions phenomena is described by combustion models which take oxidation processes in high temperature into consideration. Several models apply to auto ignition processes. AVL FIRE allows modelling knock process which occur in the combustion chamber of IC engine. This program allows for the creation of three-dimensional computational mesh, description of boundary conditions of surfaces as well as of the initial conditions simulation.

OBJECT OF INVESTIGATION

The test engine was constructed on the basis of a four-stroke compression-ignition engine S320 manufactured by “ANDORIA” Diesel Engine Manufacturers of Andrychow. After some constructional changes, this engine was redesigned for the combustion of gasoline as a spark-ignition engine. For this reason, the engine was equipped with a new fuel supply system and an ignition installation [8]. As a result of modernization, the shape of the combustion chamber and the compression ratio was reduced from 17 to 9. This is a stationary engine, equipped with two valves with horizontal cylinder configuration. The engine is equipped with a cooling system based on the evaporation of liquid.

Figures 1 and 3 show a serial engine manufactured by ANDORIA. Figure 2 shows the modernized combustion chamber with spark plug location of the test engine. On the basis of the test engine geometry the computational mesh was created (Fig. 5). Valve lifts curves were determined by measuring the engine cams. The modelling takes into account only the intake and exhaust channels located in the engine head.

Table 1. Main engine parameters

Parameters	Value
bore cylinder	100 mm
stroke piston	120 mm
connecting rod length	216 mm
direction of cylinders	horizontal
squish	11 mm
compression ratio	9
engine speed	1000 rpm
number of cylinders	1

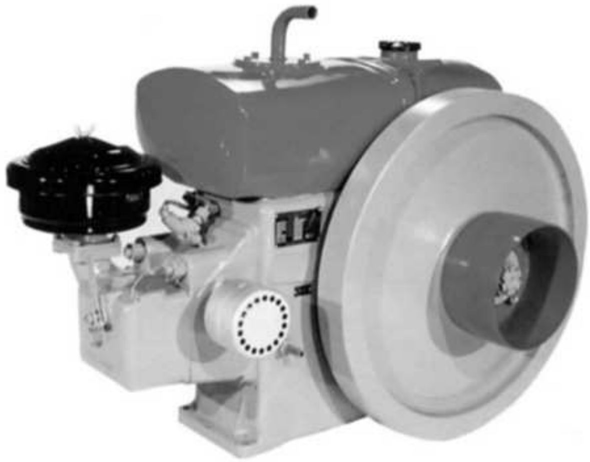

Fig. 1. Engine of S320 Andoria – catalog view

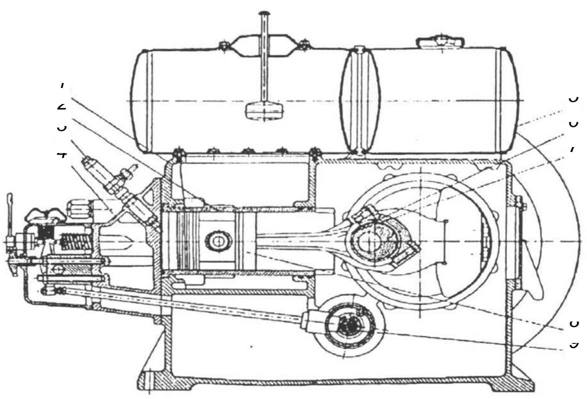

Fig. 2. Cross-section of the engine head after modernization 1 – spark plug, 2 – combustion chamber in the cylinder, 3 – combustion chamber in the piston

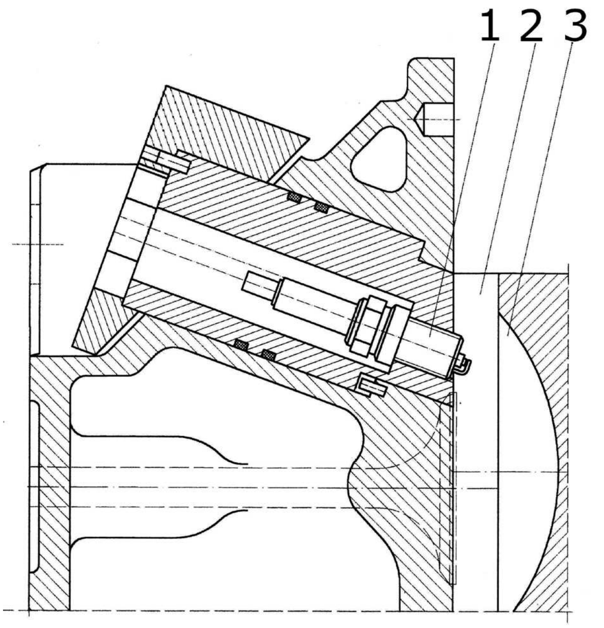

Fig. 3. Engine of S320 Andoria – cross-section of factory engine 1 – engine block, 2 – cylinder sleeve, 3 – injector, 4 – cylinder head, 5 – fuel tank, 6 – rod, 7 – crankshaft, 8 – piston, 9 – camshaft

TFSCM COMBUSTION MODEL

For the simulation of homogeneously/inhomogeneously premixed combustion processes in SI engines, a turbulent flame speed closure model (TFSCM) is available in FIRE [4]. The kernel of this model is the determination of the reaction rate based on the approach depending on parameters of turbulence, i.e. turbulence intensity and turbulent length scale, and of flame structure like the flame thickness and flame speed, respectively. The reaction rate can be determined by two different mechanisms via: Auto-ignition and Flame propagation scheme.

The auto-ignition scheme is described by an Arrhenius approach and the flame propagation mechanism depends mainly on the turbulent flame speed. The larger reaction rate of these two mechanisms is the dominant one. Hence, the fuel reaction rate ω_{fuel} can be described using a maximum operator via:

$$\omega_{fuel} = \max\{\text{Auto} - \text{ignition}\ \omega_{AI}, \text{Flame Propagation}\ \omega_{FP}\}.$$

The first scheme is only constructed for air/fuel equivalence ratios from 1.5 up to 2.0 and for pressure levels between 30 and 120 [bar], respectively. The auto-ignition reaction rate ω_{AI} can be written as:

$$\omega_{AI} = a_1 \rho^{a_2} y_{fuel}^{a_4} y_{O_2}^{a_4} T^{a_5} \exp\left(-\frac{T_a}{T}\right),$$

where: a_1 to a_5 are empirical coefficients and T_a is the activation temperature, T is the temperature, r is the density, y_{fuel} is the fuel mass fraction and y_{O2} is the oxygen mass fraction.

The reaction rate ω_{FP} of the flame propagation mechanism, the second one in this model, can be written as the product of the gas density, the turbulent burning velocity S_T and the fuel mass fraction gradient ∇y_{fuel} via:

$$\omega_{FP} = \rho S_T \nabla y_{fuel} .$$

NUMERICAL MODEL OF ENGINE

The computational mesh can be obtained as surface or volume discretization. In AVL FIRE the Finite Volume Method (FVM) is used to calculate the heat flows. For four-stroke engine four computational domains are required. The first domain includes the intake stroke until closing the intake valves. The second domain is used since the closure of the inlet valve until the exhaust valve timing, at a time when the valves are closed. The third domain is used since the opening of the exhaust valve to the end of the exhaust stroke. And finally, the fourth domain is required for the whole engine cycle. The division cycle of three domains eliminates the problem of return flows in the crevices between the valve train and valve seat.

The first step is to draw the engine workspace (Fig. 4). Due to software, valves must be slightly open. This geometry is loaded into the preprocessor of FIRE program. On the basis of this geometry the computational moving mesh is generated (Fig. 5).

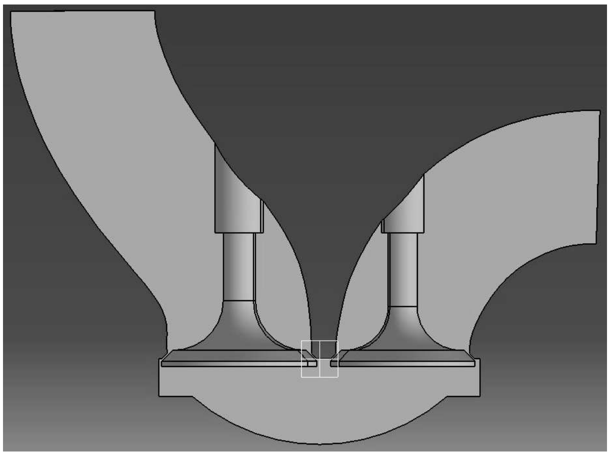

Fig. 4. Geometry of engine in CAD

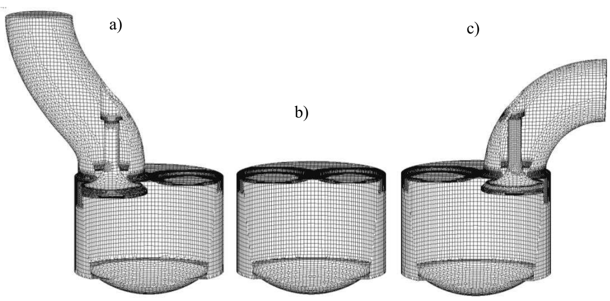

Fig. 5. Computational mesh of engine, a) intake, b) compression, c) exhaust

The computational mesh around valves was concentrated to obtain more accurate results. FIRE gives the possibility of temporary thickening of the grid.

Table 2. Modelling parameters

Parameters	Value
ignition advance angle	12 deg
fuel	gasoline
fuel temperature	320 K
initial pressure	0.095 MPa
initial temperature	365 K
excess air factor	1.0, 1.1, 1.2, 1.3
density	1.19 kg/m^3

Table 3. Submodels

Model	Name
combustion model	TFSCM
turbulence model	k-zeta-f
NO formation model	Extended Zeldovich Model
soot formation model	Lund Flamelet Model
evaporation model	Dukowicz
breakup model	Wave

RESULTS

As a result of numerical analysis a number of characteristic quantities of combustion process in the engine were obtained such as: pressure, temperature, parameters of flow field, turbulence, heat transfer, species, toxic parameters and other. In Figures 6 and 7 the results of model validation are presented. To model validation, the courses of pressure formed in real test engine were taken. As additional param-

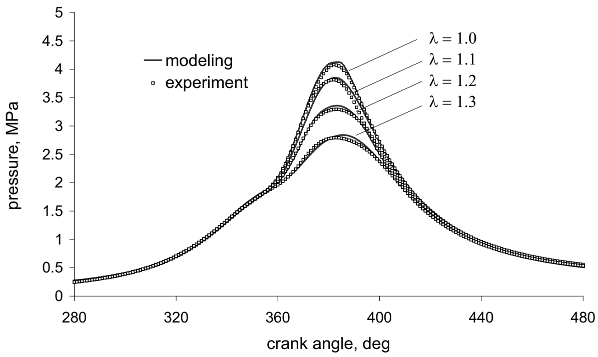

Fig. 6. Pressure courses for the four values of excess air factor

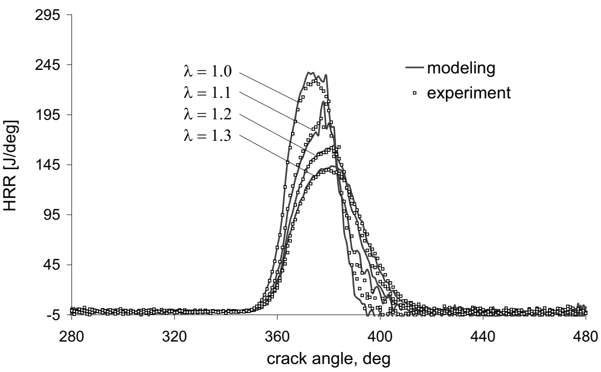

Fig. 7. Heat release rate courses for the four values of excess air factor

eters, the courses of the pressure rise and heat release rate HRR were taken as well. The researches were conducted for four values of excess air factor equal 1.0, 1.1, 1.2 and 1.3.

SI engine model of the AVL FIRE software pretty accurately reflects the real processes in the compression ignition engine. The satisfactory qualitative and quantitative compatibility between the pressure courses was achieved. For the pressure rise and heat release rate quite good agreement was achieved, as well.

Analyzing the results of modelling and experimental studies it should be mentioned that the results of indication of IC engine, in particular, the results of the analysis of thermal processes taking place in the cylinder are subject to some error resulting from the measurement accuracy and hence the uncertainty of the result.

In Figure 8 the flow field in the modelled engine during intake and compression stroke is presented. The main swirl process by the streamlines is underlined. There, the so-called tumble swirl is visible. This swirl is responsible for flame kernel direction propagation.

Figure 9 shows the cross sections of the engine cylinder where the temperature field is presented. The first three pictures show flame propagation in the combustion chamber. The direction of flame propagation is determined by fluid flows generated during intake stroke (Fig. 8). In Figure 8 the tumble flow is highly visible. The other two pictures show the exhaust stroke when the exhaust valve starts to open and when it is fully open.

CONCLUSIONS

AVL FIRE program is a research tool that can be successfully used to model the thermal cycle of the internal combustion engine. The AVL FIRE up-to-date numerical code used during research made it possible to generate 3D geometric mesh of combustion chambers of the test engine and allowed to perform numerical calculations of processes occurring in this engine. Simulations of combustion process have delivered information concerning spatial and time-de-

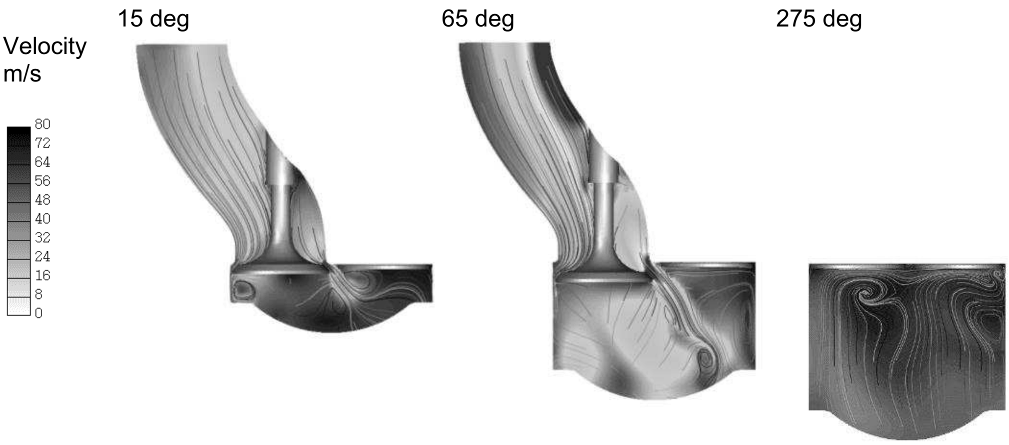

Fig. 8. Cross sections of the engine cylinder during intake and compression stroke – velocity field with streamlines

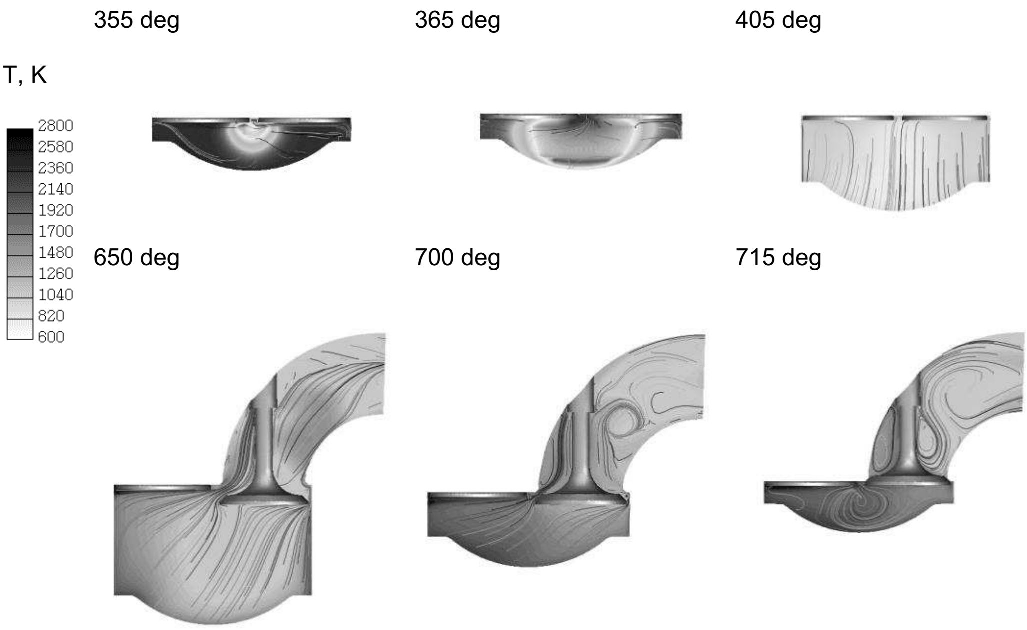

Fig. 9. Cross sections of the engine cylinder at the beginning of combustion and during exhaust stroke – temperature

pendent pressure and temperature distribution in combustion chamber. This information would be extremely difficult to obtain by experimental methods. It allows analyzing not only the combustion chamber but also the intake and exhausting process.

The paper presents results of SI engine modelling using CFD software. Pressure, temperature, heat release rate and other parameters in function of crank angle as well as spatial distribution of the above-mentioned quantities at selected crank angles were determined. The created model of SI engine was successfully verified. The resulting differences are acceptable. The results of modelling allow for an analysis of engine operation both in terms of thermodynamic and flow.

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WALIDACJA MODELU BADAWCZEGO SILNIKA ZI

Streszczenie. W pracy przedstawiono wyniki modelowania obiegu cieplnego tłokowego silnika spalinowego o zapłonie iskrowym. Modelowanie przeprowadzono w programie AVL Fire. Obiektem badań był silnik S320 o zapłonie iskrowym zasilany benzyną. Au-

tor pojął trud wygenerowania kompletnej siatki dla posiadanego silnika spalinowego, z uwzględnieniem kanałów wymiany ładunku wraz z zaworami. Wymagało to wygenerowania czterech domen obliczeniowych. Uwzględniono miejscowe i chwilowe zagęszczanie siatki, co przyczyniło się do uzyskania dokładniejszych rozwiązań oraz skrócenia i tak długiego czasu obliczeń cyklu silnika. Wyniki analizy numerycznej zostały zestawione z wynikami indykowania silnika na stanowisku badawczym. Stworzony model silnika SI został pomyślnie zweryfikowany.
Słowa kluczowe: silnik, symulacja, modelowanie, spalanie.

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