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A LES numerical approach for investigating the cycle-to-cycle combustion pressure variability in a direct injection gasoline engine

The Large Eddy Simulation method (LES) has become a powerful computational tool for the application to turbulent flows. It links the classical Reynolds Averaged Navier–Stokes (RANS) approach and Direct Numerical Simulation (DNS). This means that the large eddies are computed explicitly in a time-dependent simulation using the filtered Navier-Stokes equations. The LES resolves the large flow scales that depend directly on the geometry where the small scales are modelled by the sub-grid-scale models. LES is expected to improve the description of the aerodynamic and combustion processes in Internal Combustion Engines.

This paper addresses the topic of developing the combustion model GCM (Gradient Combustion model) for the Large Eddy Simulation (LES) method. Another part of this paper presents numerical investigations of cycle-to-cycle combustion pressure variability with comparison to experimental data. The Gradient Combustion model (GCM) based on the Turbulent Flame Speed Closure Model (TFSCM) is validated against the experimental data for a multi-cycle gasoline direct injection research engine (SCRE). It is shown that the introduced combustion model is stable and capable of proper representation of the experimental results which is one of the assets of the LES method.
Keywords: *gasoline engine, direct injection, cycle-to-cycle variability, LES, combustion, SCRE*

Metoda LES jako narzędzie do analizy fluktuacji cisnienia dla kolejnych cykli pracy w silnikach benzynowych o wtrysku bezpośrednim

Metoda LES jest obecnie zaawansowanym narzędziem numerycznym do analizy przepływów turbulentnych. Metoda LES opiera się na połączeniu klasyczej metody uśredniania równań Naviera-Stokes (RANS) z bezpośrednią analizą numeryczną (DNS). Oznacza to, że duże struktury wirowe są rozwiązywane niejawnie poprzez filtrowanie równań Naviera-Stokesa. W metodzie LES oznacza to obliczanie przepływu dużej skali, który zależy od geometrii, podczas gdy przepływ w małej skali jest modelowany modelem podsiatkowym (ang. Sub-grid-scale models, SGS). Uważa się, że metoda LES pozwoli na poprawienie numerycznego opisu aerodynamiki i procesów spalania w silnikach tłokowych.

Artykuł przedstawia wyniki prac rozwojowych nad modelem spalania w metodzie LES. Model GCM (model spalania oparty na metodzie gradientu) został zastosowany do obliczeń wielocyklicznych i ich weryfikacji z wynikami eksperymentalnymi. Wyniki eksperymentalne pozyskano z badań na jednocylindrowym silniku badawczym (SCRE) o wtrysku bezpośrednim. W pracy pokazano, że model spalania jest stabilny numerycznie oraz otrzymane wyniki są zgodne z wynikami eksperymentalnymi, co jest jedną z ważniejszych zalet metody LES.
Słowa kluczowe: *wtrysk bezpośredni, fluktuacje cykliczne, LES, spalanie, silnik benzynowy, SCRE*

1. Introduction

This paper addresses the topic of developing of combustion model in Large Eddy Simulation (LES) method for cycle-to-cycle combustion variation in spark ignition gasoline direct injection engine. Basing on the Turbulent Flame Speed Closure Model (TFSCM) [1], which relies on a gradient method for flame tracking and reaction rate control and new turbulent burning velocity equation [2] the Gradient Combustion Model (GCM) was prepared for the calculation. As a result the turbulent burning velocity is influenced by the fluctuation velocity which is resolved by sub-grid scale (SGS) model. By means of the SGS the Smagorinsky model was used .

Simulation results for a single cylinder spark ignition research engine (SCRE) with direct gasoline injection for one working point were compared with experimental results. It is shown that Gradient Combustion Model in this early development stage is capable of proper representation of the experimental results, is stable for the multi-cycle calculations and can predict cycle-to-cycle variability which is one of the assets of the LES method.

2. Combustion model

The source term of the species transport eq. is presented by:

$$\overline{S}_c = \rho_u \cdot S_t \cdot \left| \nabla \widetilde{c} \right| \qquad (1)$$

where ρ_u is a density of unburnt mixture, S_t is a turbulent burning velocity solved for the SGS scale, $\left| \nabla \overline{c} \right|$ is a gradient progress variable. The equation describing the turbulent burning velocity, Yakhot formula [2]:

$$S_t = S_u \left(Y_{H_2}, T, p \right) \cdot \left(\psi \cdot \chi_{Karl_{MAX}} \right) \cdot \exp \left(\frac{u_{sgs}}{S_t} \right)^2 \qquad (2)$$

where S_u is the laminar burning velocity calculated as a function of temperature and pressure, χ_{Karl} is a Karlovitz factor representing the flame generated turbulence and u_{sgs} is a local SGS velocity of the flow calculated with use of Smagorinsky SGS model. The maximum Karlovitz factor is defined by [4]:

$$\chi_{Karl \max} = \frac{E - 1}{\sqrt{3}} \qquad (3)$$

The expansion coefficient represents the ratio of the unburned mixture density to the burned mixture density:

$$E = \rho_u \Big/ \rho_b \qquad (4)$$

The presented combustion model is easy to adopt for the other SGS turbulence models. The chemical reaction process is described by mean of one chemical reaction equation.

3. The SCRE experimental and simulation setup description

To investigate the cycle-to-cycle condition variability by mean of pressure difference the experiments were conducted at AVL. For this task the AVL single cylinder research engine FM540 was selected (Fig. 1). Load point setup for experimental and simulation tasks is presented in table 1. In Fig 2. experimental pressure results are presented for 27 cycles.

For the purpose of numerical calculations the 3D models of the SCRE engine has been prepared which is presented in Fig. 3. The iso-octane as reference gasoline fuel was used in simulation tasks.

All the calculations where made with use of the AVL FIRE® software by implementing the GCM with the use of user function. The LES flow description, spray models, thermodynamic data are calculated by the FIRE® solver, GCM is responsible for providing the source term in fuel species trans-

port equation. With the use of GCM the reaction rate is determined.

The Large Eddy Simulation (LES) as adopted in the present work is based on the filtered instantaneous Navier-Stokes equations. Filtering operation actually represents scale separation in space, where large scales are directly resolved and the influence of small scales is taken into account by the sub-grid scale (SGS) model. In practice, it is assumed that filter is actually defined by the computational mesh resolution.

The sub-grid scale stress tensor is modelled according to the well-established Smagorinsky model [3]:

$$\tau_{ij} - \frac{\delta_{ij}}{3} \tau_{kk} = -2 \nu_{sgs} \overline{S}_{ij} \qquad (5)$$

with the sub-grid scale viscosity written as

$$\nu_{sgs} = (C_s f \Delta)^2 \left| \overline{S} \right| \qquad (6)$$

and the value of the model constant $C_s = 0.1$, while the resolved rate-of-strain tensor is defined as $\left| \overline{S} \right| = (2 \overline{S}_{ij} \overline{S}_{ij})^{1/2}$.

The filter width, Δ, is defined as $\Delta = (Vol)^{1/3}$, where Vol is the volume of the computational cell. Near the wall, a wall damping function of Van Driest type is adopted to account for the reduced growth of small scales near the wall, thus

$$f = 1 - \exp(-\frac{y^+}{25}) \qquad (7)$$

The spray model adopted in the present study is based on the Lagrangian Discrete Droplet Method (DDM) [5]. In the DDM the continuous gaseous phase is described by the standard Eulerian conservation equations, whereas the transport of the dispersed phase is calculated by tracking the trajectories of representative droplet parcels. A parcel consists of a number of droplets, with all the droplets having identical physical properties and behaving equally when they move, break up, hit a wall or evaporate. The calculation of the parcel movement is done with a sub-cycling procedure between the gas phase time steps taking into account the forces exerted on the parcels by the gas phase as well as the related heat and mass transfer. The coupling between the liquid and the gaseous phases is achieved by source term exchange for mass, momentum, energy and turbulence. For the present LES application, turbulent dispersion effects are assumed to be fully covered by the interaction of the droplets with the resolved LES flow field scales.

The liquid fuel spray characteristics resulting from primary atomization is approximated in the present study by prescribing the droplet size, velocity and spray angle at the nozzle exit. Secondary atomization, i.e. droplet break-up due to their interaction with the gas flow is modelled according to the well-known WAVE break-up approach, droplet evaporation is modelled according to [5]. Particle interaction processes are assumed to be negligible due to the dispersed nature of the liquid fuel spray downstream of the primary break-up region, a wall interaction model accounts for sticking, sliding and reflection of droplets depending on the droplet velocity and impingement angle.

Figure 1. AVL Single cylinder engine FM540

Table 1. Engine load point setup for experimental and simulation tasks.

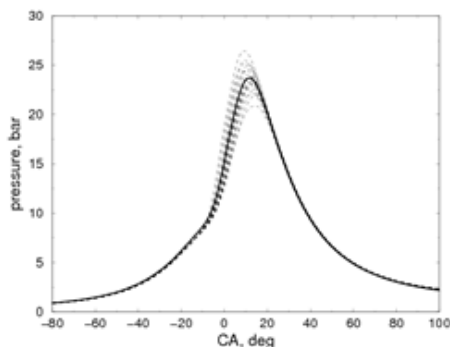| Type	GDI NA
Displacement	500 cm³
Bore	86 mm
Stroke	86 mm
Compression Ratio	11.5
Injector	Side mounted GDI injector, double injection capability
RPM	2000
IMEP	3.6 bar
Spark timing	17° bTDC
EVO	44° bBDC
EVC	14° bTDC
IVO	21° aTDC
IVC	52° aBDC

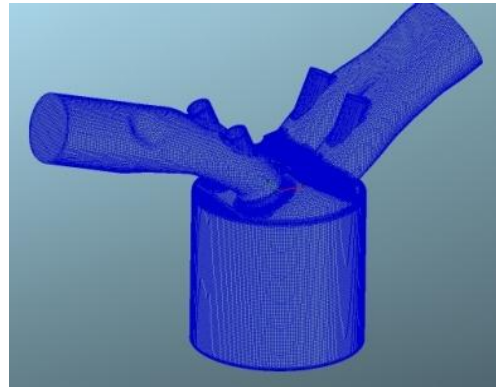Figure 2. Pressure cycle-to-cycle variation experimental results.

Figure 3. Mesh model of the SCRE Engine

4. Results

Multi-cycle simulations despite the time consuming characteristic are source of many flow and combustion data results. At first the flow field changes can be observed in fig. 4 for IVC time event. It is clearly seen that from cycle-to-cycle the flow field characteristic changes by means of the main vortex position and the shape. Vermorel at al. [6] wrote that cycle-to-cycle fluctuations are caused by variation for intake (injection and mixture preparation) and compression stroke.
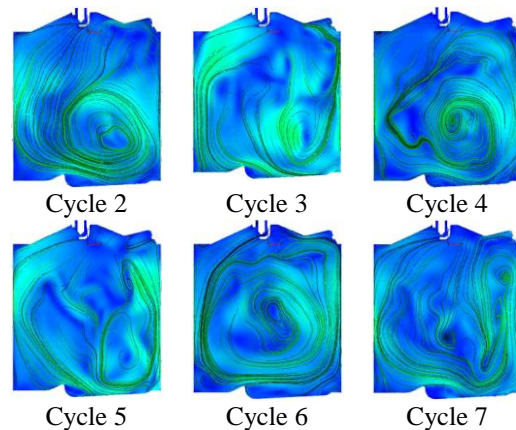

Figure 4: Velocity flow field cycle-to-cycle variation after IVC.

Such different conditions influence the combustion processes and can be seen also in this study, for example for mixture formation (fig. 5).

With the use of the flame front view by mean of reaction rate it was possible to compare the shape of flame for different cycles. In fig. 6 and fig. 7 it is shown how different the result can be for the same combustion model. The influence of the flow field, with the local velocity close to combustion burning velocity stops the flame front propagation before TDC and this can be seen for both cycles. The shape of the flame front can be seen for XY cross

section. The GCM and LES model allows obtaining irregular flame front characteristic with possibility to roll up, which means flame-to-flame interaction.
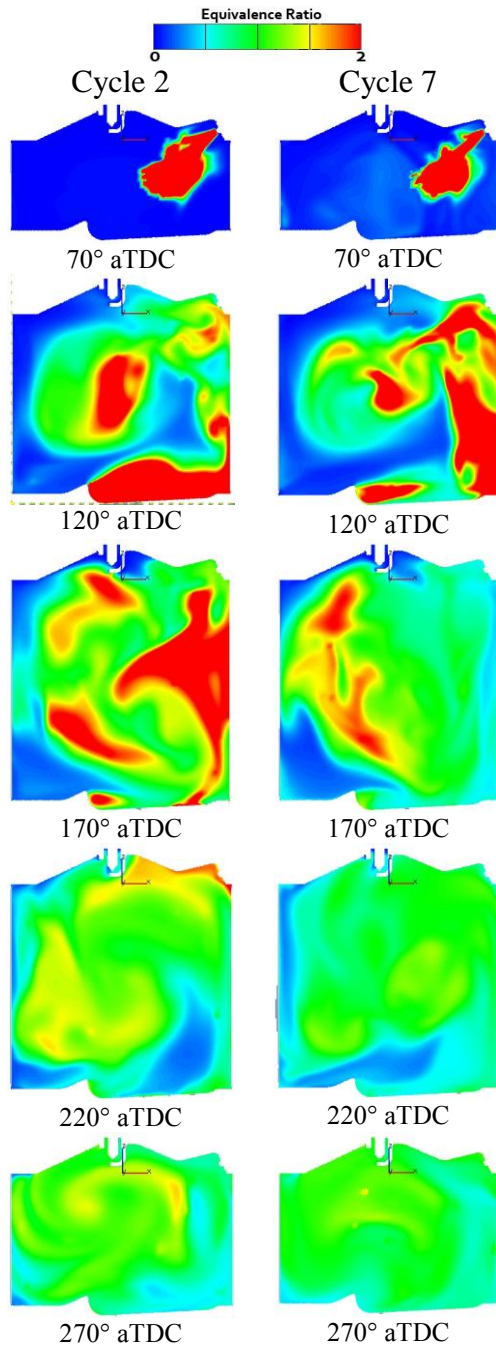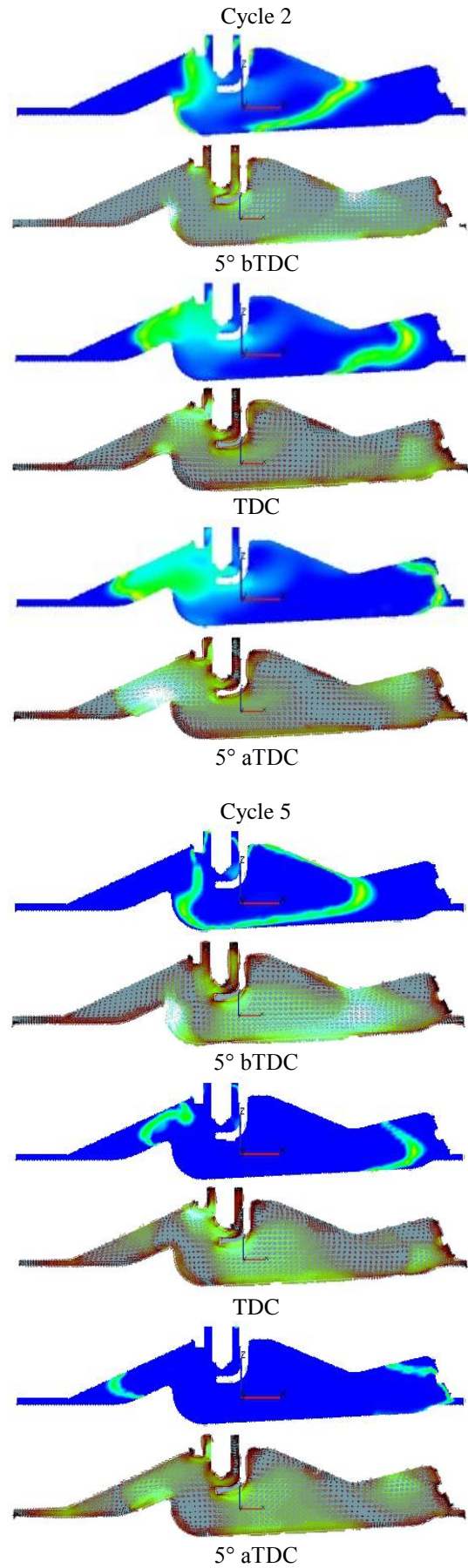
Cycle 2

5° bTDC

TDC

5° aTDC

Cycle 5

5° bTDC

TDC

5° aTDC

Cycle 2 · Cycle 7

70° aTDC · 70° aTDC

120° aTDC · 120° aTDC

170° aTDC · 170° aTDC

220° aTDC · 220° aTDC

270° aTDC · 270° aTDC

Figure 5: Equivalence ratio view in XZ plane for 2nd and 7th cycle.
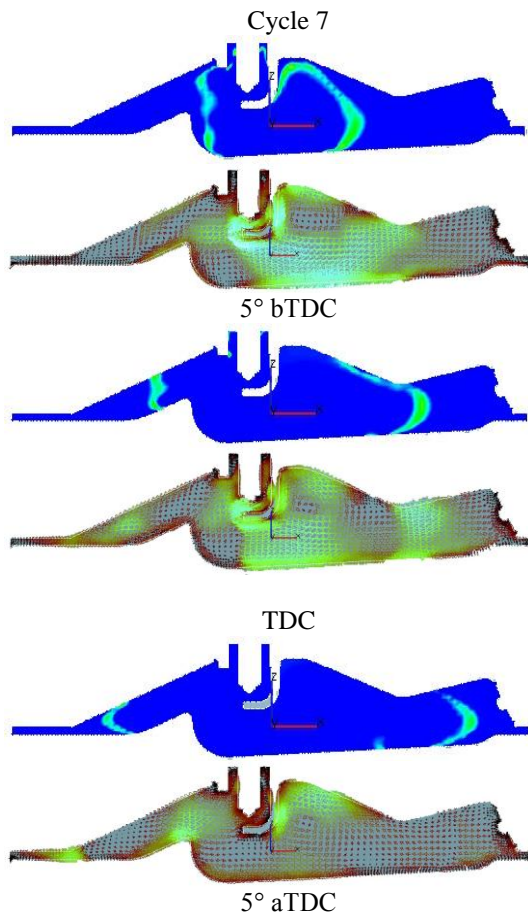
Cycle 7

5° bTDC

TDC

5° aTDC

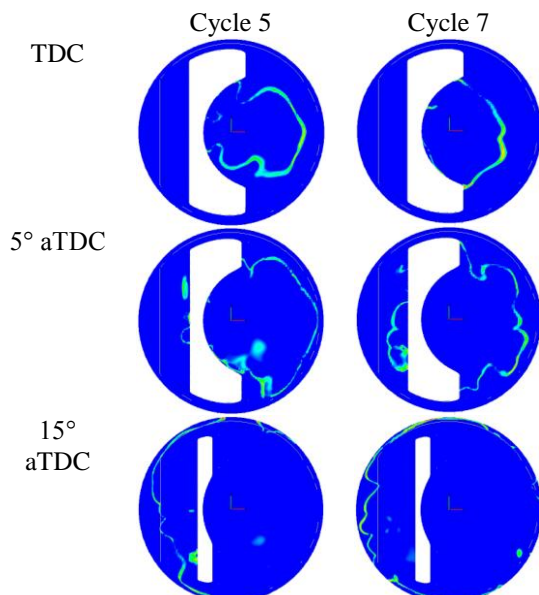*Figure 6: Flame front and velocity flow field view in XZ plane for 2nd, 5th and 7th cycle.*

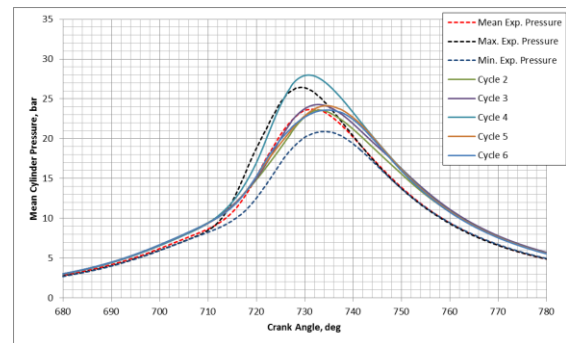*Figure 7. Flame front view in XY plane for 5th and 7th cycle.*

Figure 8. Mean pressure simulation results.

In fig. 8 the mean pressure results are presented for experimental and simulation data. The first simulation cycle is not shown because the result data are influenced by initial conditions. All cycles are in experimental range results except the data from cycle 4 which gives higher pressure and faster reaction progress in comparison to other results.

Results from simulations of cycle-to-cycle variation in SCRE engine are in good agreement to experimental data in overall but because that GCM is in early stage of development there is still a need for further development work.

5. Discussion

One of the most challenging problems in fluid dynamics is the proper description of fluid flow and combustion. In those processes for ICE local high density and velocity gradient can be found, which is also a problem for proper volume discretization and phenomena description. Fluid flow in the cylinder is turbulent, cyclic and time dependent. The combustion process is influenced by mixture preparation by means of intake stroke and injection event.

In research on cycle-to-cycle fluctuations for ICE by Goryntsev et al.[7] it was shown that cyclic variation cannot be treated separately and are highly connected to turbulence description. Random characteristics of the turbulence are source of velocity flow variation in combustion chamber. In theory strategy for one cycle calculation can be done only properly only with use of LES method. But as for RANS also in LES such results depend on initial conditions. This means that only with accurate initial conditions [8] one cycle calculation approach is possible. So the conclusion is that with multi-cycle calculation and LES method simulation results are the most accurate [6], which was also shown in this work. RANS method for multi-cycle calculations will lead to stabilization of the results and after the number of cycles the constant results will be reached in cycle domain. By RANS method the mean value results can be found, in LES method cycle-to-cycle variation can be investigated.

It was shown in this work that LES method allows to describe with good accuracy cyclic and time dependent fluid flow in comparison to RANS

method. Further development work on LES method and LES combustion model, like GCM, will allow to simulate more complicated combustion tasks. By LES method it is possible to get proper data results in combustion engine, despite that the method is computational and power consuming. LES method with use of multi-cycle simulation is a future engine development tool, which can be used for improvement of processes efficiency and emissions.

6. Acknowledgments

Nomenclature/*Skróty i oznaczenia*

LES   Large Eddy Simualtion/*symulacje dla wirów wielkoskalowych*
SGS   Sub-grid Scale/*Skala podsiatkowa*
RANS Raynolds Average Navier-Stokes Equation/*równania N-S*
ICE   Internal Combustion Engine/*silniki spalania wewnętrznego*
ER   Equivalence ratio/*współczynnik stechiometrii*
TDC   Top dead center/*górne martwe położenie*
BDC   Botton dead center/*dolne marrtwe położenie*

EVO   Exhaust Valve opening/*Kąt otwarcia zaworu wylotowego*
EVC   Exhaust Valve closing/*Kąt zamknięcia zaworu wylotowego*
IVO   Inlet Valve opening/*Kąt otwarcia zaworu dolotowego*
IVC   Inlet Valve closing/*Kąt zamknięcia zaworu dolotowego*
DDM   Discrete Droplet Model/*Dyskretny model kropli*

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