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MONITORING OF CHANGE IN VOLUMES FOR DIESEL ENGINE IN-CYLINDER PROCESS WITH QUASI-DIMENSIONAL NUMERICAL MODEL

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Abstract: *Distribution of volumes and their change in the diesel engine cylinder is an essential parameter of each numerical model. Quasi-dimensional numerical model divide space inside the engine cylinder into two main areas: fuel spray packages and a large surrounding area without combustion, which is used for air distribution into the fuel spray packages. This paper analyzes the four-stroke diesel engine for the light truck drive in several operating modes. Numerical model is validated by using laboratory measurements. In a selected engine operating mode are presented the results of a numerical model for the observed volumes inside the engine cylinder. The observed volume change provides insight into the details of the air-fuel mixing process and fuel evaporation. Described changes are the basis for the calculation of heat-release and pressure changes in the cylinder. The developed numerical model provides insight into the details of the process inside the engine cylinder which cannot be measured with standard measuring equipment.*
Keywords: *FUEL SPRAY, ZONE WITHOUT COMBUSTION, LIQUID FUEL, THERMODYNAMIC VOLUME*

1. Introduction

Quasi-dimensional (QD) numerical models for internal combustion engine (ICE) simulations were developed in order to achieve a compromise solution between Zero-dimensional (0D) and Computational fluid dynamics (CFD) numerical models. While 0D models use a homogeneous mixture of gases in the cylinder [1], CFD models provide the most detailed simulations, but with long calculation time [2].

Calculation start for a QD numerical model begins at the start of fuel injection. Each fuel spray must be divided into spray packages and new spray packages are created as injection continues, until its end, Fig.1. Every spray package is monitored through 3 indexes: index along the symmetry axis of the nozzle (*i*), index vertical to the symmetry axis of the nozzle (*j*) and index (*k*) for each fuel spray if the injector has several nozzles. Around the fuel sprays is a zone without combustion (zone of fresh air) - (ZWC) [3].

The QD model main assumption is that between spray packages is not allowed any exchange of mass or energy. The only necessary mass exchange is the air entrainment from the zone without combustion (ZWC) into spray packages [4], when the required conditions are fulfilled.

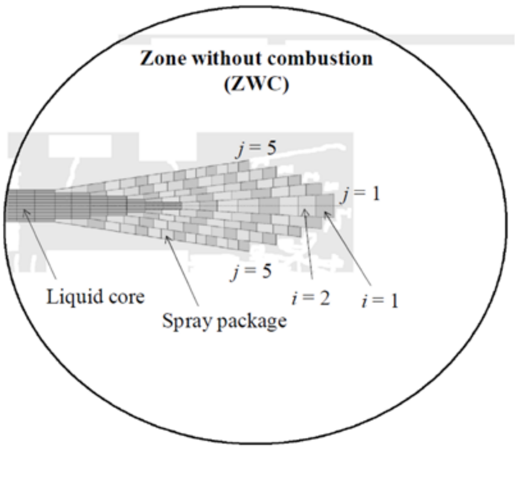

Fig.1. *Cross-section of the cylinder in the QD numerical model*

2. Numerical model

Numerical model equations were designed for a direct calculation of pressure and temperature changes in the cylinder, without the need for numerical iterations. The complete numerical model development, along with its main equations is presented in [5]. It can be used for simulation of a range of direct injection diesel engines, not only a high speed, but also for ship two-stroke slow speed diesel engines [6].

Equations are calculated for the thermodynamic (TD) volume of each package (only the volume of gases and vapors in the package). The package thermodynamic volume is the geometric package volume without the volume of liquid fuel. In the zone without combustion (ZWC) is not present any amount of liquid fuel, so its geometric volume is always equal to its thermodynamic volume.

The properties of liquid fuel in the fuel spray package are monitored by separate, independently developed mathematical models. Liquid fuel energy conservation equation is used for monitoring the temperature of liquid fuel, basic parameter for the fuel evaporation simulation. In QD numerical model fuel vapor is considered as an ideal gas in the gaseous mixture with other species.

Combustion chamber geometric volume and its change define kinematics of crankshaft mechanism. Geometric volume is reduced to the volume of injected liquid fuel and the resulting volume was used in the equations related to the thermodynamic processes.

The total geometric volume of any fuel spray package will be $V_{g,k,i,j}$, while the geometric volume of ZWC will be V_{ZWC}. The liquid fuel volume inside each fuel spray package ($V_{lf,k,i,j}$) will be:

$$V_{lf,k,i,j} = \frac{m_{lf,k,i,j}}{\rho_{lf,k,i,j}} \tag{1}$$

where m_{lf} and ρ_{lf} are the mass and density of liquid fuel.

The thermodynamical volume of the same fuel spray package ($V_{td,k,i,j}$) is:

$$V_{td,k,i,j} = V_{g,k,i,j} - V_{lf,k,i,j} \tag{2}$$

The sum of the geometric volumes is equal to the total volume of the combustion chamber ($V_g(\varphi)$):

$$V_g(\varphi) = V_{ZWC} + \sum_k \sum_i \sum_j V_{g,k,i,j} \tag{3}$$

where φ is crank angle.

Total thermodynamical volume for the entire combustion area ($V_{td}(\varphi)$) is the actual geometric volume reduced by the total current volume of liquid fuel:

$$V_{td}(\varphi) = V_g(\varphi) - \sum_k \sum_i \sum_j \frac{m_{lf,k,i,j}}{\rho_{lf,k,i,j}} \tag{4}$$

The rate of change in cylinder thermodynamic volume is defined by the kinematics of crankshaft mechanism and with a speed of change in liquid fuel total volume. Liquid fuel total volume is changed during injection, evaporation and re-condensation. In this QD model, the effect of the change in the liquid fuel volume caused by thermal volume dilation is neglected:

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$$\frac{dV_{td}(\varphi)}{d\varphi} = \frac{dV_g(\varphi)}{d\varphi} - \sum_k \sum_i \sum_j \frac{1}{\rho_{lf,k,i,j}} \cdot \left(\frac{dm_{lfi,k,i,j}}{d\varphi} - \frac{dm_{vap,k,i,j}}{d\varphi} + \frac{dm_{rc,k,i,j}}{d\varphi} \right) \quad (5)$$

where index "lfi" denotes injected liquid fuel, index "vap" denotes fuel vapor and index "rc" denotes liquid fuel re-condensation.

In the last part of the equation (5) must be taken into account signs in parentheses that are related to liquid fuel. Liquid fuel mass inflow in the above equation has positive sign (fuel injection and re-condensation) since they increase the volume of liquid fuel, while evaporation reduces the volume of liquid fuel, and has a negative sign. The signs that apply to liquid fuel are opposite when considering the volume of gaseous section.

The rate of change in total thermodynamic volume for the entire engine cylinder is defined by:

$$\frac{dV_{td}(\varphi)}{d\varphi} = \frac{dV_{ZWC}(\varphi)}{d\varphi} + \sum_k \sum_i \sum_j \frac{dV_{td,k,i,j}(\varphi)}{d\varphi} \quad (6)$$

The rate of change in thermodynamic volume in the zone without combustion (ZWC) is:

$$\frac{dV_{ZWC}(\varphi)}{d\varphi} = \frac{dV_{proc,ZWC}(\varphi)}{d\varphi} + \frac{1}{\rho_{acp}} \sum_k \sum_i \sum_j \left(\frac{dm_{acp,k,i,j}}{d\varphi} \right) \quad (7)$$

where index "acp" denotes the mixture of clean air and combustion products which remain in the cylinder from the previous combustion process.

The rate of change in thermodynamic volume in the spray package:

$$\frac{dV_{td,k,i,j}(\varphi)}{d\varphi} = \frac{dV_{proc,k,i,j}(\varphi)}{d\varphi} + \frac{1}{\rho_{acp}} \frac{dm_{acp,k,i,j}}{d\varphi} - \frac{1}{\rho_{lf,k,i,j}} \cdot \left(\frac{dm_{lfi,k,i,j}}{d\varphi} - \frac{dm_{vap,k,i,j}}{d\varphi} + \frac{dm_{rc,k,i,j}}{d\varphi} \right) \quad (8)$$

In equations (7) and (8) index "proc" refers to a process volume change due to the cylinder process thermodynamics. It is calculated as the difference between the current and previous volume, divided by the angular integration step.

3. Engine specifications and measurement results

Investigated diesel engine was a high speed direct injection turbocharged engine MAN-D-0826-LOH15, Table 1. The measurements were performed in the Laboratory for Internal Combustion Engines and Electromobility, Faculty of Mechanical Engineering, University of Ljubljana, Slovenia.

Table 1. *Engine specifications*

Displacement	6.87 l
Number of cylinders	6
Peak power	160 kW
Cylinder bore	108 mm
Stroke	125 mm
Crank radius	62.5 mm
Compression ratio	18
Nozzle diameter	0.23 mm
Number of nozzle holes	7
Combustion chamber	Bowl in piston

During the measurement period, the engine was connected to an eddy current brake Zöllner B-350AC. For the brake control is used a control system KS ADAC/Tornado, which producer is Kristl, Seibt & Co.

Laboratory measuring sensor AVL GH12D was used for the cylinder pressure measuring. This sensor was placed in an extra hole in the cylinder head.

For the analysis of change in volumes in the QD numerical model, several measurement sets were made. The selected set of measurements is presented in Table 2.

Table 2. *The measurement results (MAN-D-0826-LOH15)*

O.P.*	Fuel consumption (kg/h)	Air consumption (kg/s)	Rotational speed (min^{-1})	Power (kW)
1	9.198	0.100764	1498	43.78
2	18.040	0.126717	1502	89.32
3	14.773	0.191578	2401	56.27
4	28.841	0.260685	2399	126.05

* Operating Point

Simulations with developed numerical model were done at each presented operating point. Except a detailed calculation of in-cylinder volumes change, the model calculates a large number of different engine parameters, for each spray package and also for the zone without combustion. In this paper is presented numerical model results for operating point 2.

4. Numerical model results and discussion

Fig.2. shows the change in thermodynamic volume of the entire observed engine cylinder. Cylinder thermodynamic volume decreases in the phase of compression (until 360 °CA) and increases during the phase of cylinder expansion.

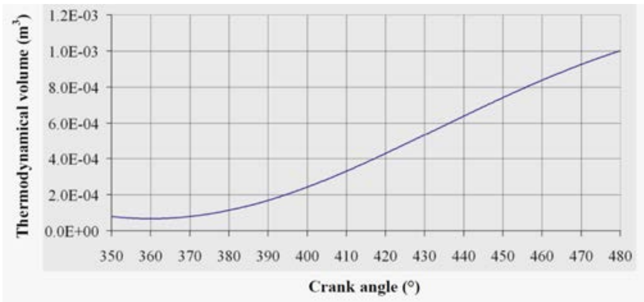

Fig.2. *Change in thermodynamic volume for the entire engine cylinder*

Fig.3. presents thermodynamic volume rate of change for the entire engine cylinder and for the ZWC. In order to explain the volume rate of change for ZWC, in Fig.4. is presented a change in the overall ZWC volume.

At the beginning of the operating substance entrance from the ZWC in spray packages, the volume of the zone without combustion decreases, proportional to the volume of operating substance which enters in all spray packages of all fuel sprays. ZWC discharge becomes more intense as the spray packages advance through the cylinder while at the same time the expansion in the cylinder increases the volume of the zone without combustion. The result is that the cylinder expansion has a greater effect on the volume of a ZWC than cumulative discharge of operating substance in the spray packages, thus volume rate of change for ZWC become positive and the total volume of the zone without combustion increases in this area.

While expansion in the cylinder continues, operating substance volume discharge from ZWC into the spray packages becomes more intense than the ZWC volume increase caused by a cylinder expansion, so the volume rate of change in the ZWC becomes negative, and the volume of the zone without combustion decreases. The ZWC total volume reduction in this area is also caused because

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of spray packages volume increase what will further reduce the volume of the zone without combustion.

Just before 470 °CA is achieved the minimum operating substance mass in the ZWC and the ZWC volume, which corresponds to the minimum mass, remains constant until the exhaust valves opening. Increase in volume caused by cylinder expansion from that moment on causes increase in a volume of each spray package and has no influence on the volume of ZWC.

In developed quasi-dimensional numerical model has been introduced such numerical limit in order to prevent the occurrence that in the spray packages enter the nonexistent mass of operating substance from the ZWC.

At the moment of the exhaust valves opening, all the zones inside cylinder (all spray packages and ZWC) are mixed and so mixed exits from the cylinder to the engine exhaust.

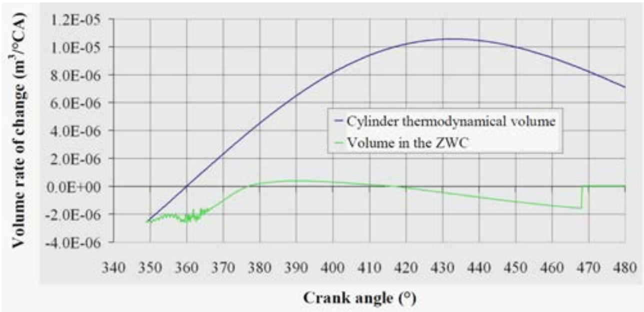

Fig.3. *Thermodynamic volume rate of change in the cylinder and in the ZWC*

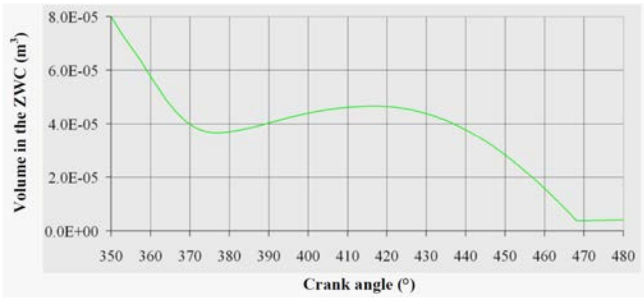

Fig.4. *Volume change in the ZWC*

Although in the ZWC fuel evaporation and combustion does not occur, characteristics and properties of the operating substance in this zone significantly influenced the processes in spray packages, during an exchange of operating substance from ZWC to spray packages. Any error in the operating substance properties calculation for the ZWC can significantly disrupt the processes of fuel evaporation, fuel vapor mixing with the air and the combustion, so the results obtained by the simulation would not be correct.

Inside the QD numerical model is developed sub-model for calculating operating substance's thermodynamic properties in every observed calculation step. The results of this sub-model are compared with results presented in [7] and deviations in the results have not been observed.

Thermodynamic properties sub-model enable insight into the change of important operating substance characteristics, not only in the ZWC, but also in every fuel spray package. The next four figures present some results of this sub-model for the zone without combustion.

The density of the gaseous operating substance in the zone without combustion, Fig.5., increases during the phases of compression and at the start of combustion, followed by decrease due to cylinder expansion and discharge of the operating substance into the spray packages.

The adiabatic exponent in the zone without combustion, Fig.6., decreases during compression and at the beginning of combustion after which increases during the expansion. Just before the moment of exhaust valves opening, adiabatic exponent of operating substance in the ZWC becomes almost equal to the adiabatic exponent of air.

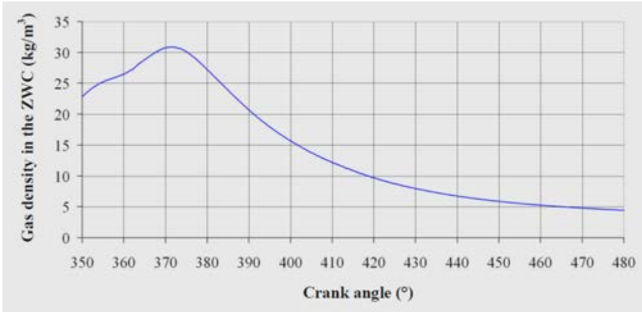

Fig.5. *Change in gas density in the zone without combustion*

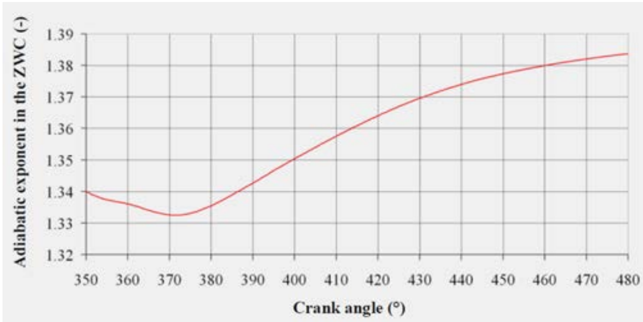

Fig.6. *Change in adiabatic exponent in the zone without combustion*

Not only the equilibrium molar concentration of O_2, but also all the other equilibrium molar concentrations in the ZWC shows the same trend-they increase during the fuel evaporation and at the beginning of combustion they started to decrease and decreases until the opening of the exhaust valves, Fig.7.

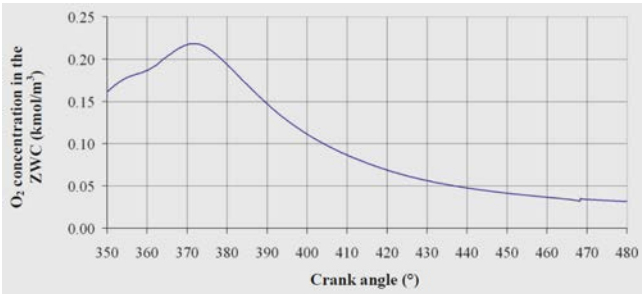

Fig.7. *The equilibrium molar concentration of O_2 in the zone without combustion*

Fig.8. shows kinetic molar concentration of NO in the zone without combustion. Kinetic molar concentration of nitric oxide in the ZWC is very important for the calculation of the total emission of nitrogen oxides, from the entire investigated diesel engine.

Kinetic molar concentration of nitric oxide in the ZWC grows slowly, until the moment just before the opening of the exhaust valves. At that moment NO kinetic molar concentration suddenly increases and finally partially reduces from its maximum value at the moment of exhaust valves opening.

Among other volumes, it is yet interesting to show the change in total volume of liquid fuel in the cylinder (sum for all spray packages), as presented in Fig.9.

The total volume of liquid fuel in the cylinder initially increases during fuel injection. When fuel evaporation starts, the volume of liquid fuel starts to decrease. The liquid fuel volume decrease is

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more significant as evaporation becomes more intense. At the moment when fuel evaporation finished, the volume of the liquid fuel becomes equal to zero.

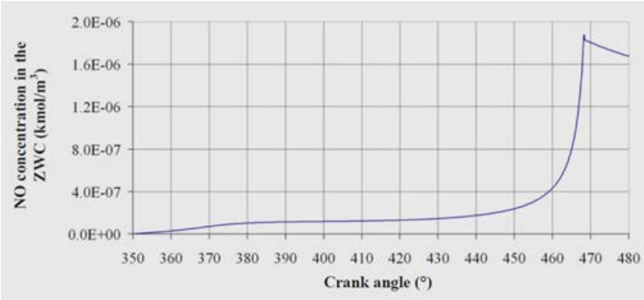

Fig.8. *The kinetic molar concentration of NO in the zone without combustion*

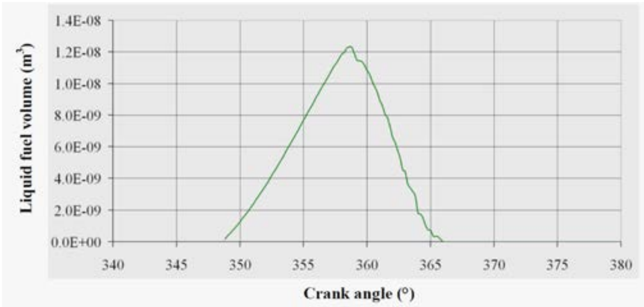

Fig.9. *Change of liquid fuel total volume in the entire cylinder*

5. Conclusion

Volumes change and distribution in the diesel engine cylinder is a very important element of each numerical model, as is the case of presented QD numerical model.

Change in volumes inside the cylinder gives insight into details of in-cylinder process, what is essential to provide accurate and precise numerical simulation results. Volumes inside the cylinder, according to QD model specifications, are divided in two main parts: fuel spray packages and zone without combustion.

As the zone without combustion contains mostly air, it would be wrong to assume that it's operating substance thermodynamic characteristics and volume change does not have a major impact on several important processes, as air-fuel mixing process and fuel evaporation.

In this paper is presented not only cylinder and ZWC thermodynamic volume change, it is also presented some important operating substance thermodynamic characteristics change inside ZWC, calculated with separately developed numerical sub-model. Knowledge of operating substance thermodynamic property changes in the ZWC is important not only for mentioned processes, but also for the accurate calculation of emissions (primarily NO_x and Soot) from one cylinder and from the entire engine.

Liquid fuel does not participate in the thermodynamic volume of the cylinder, so its properties were calculated with separate developed mathematical models. One of the results for the liquid fuel numerical model is also presented in this paper.

The developed numerical model provides insight into the details of the process inside the engine cylinder which usually cannot be monitored with standard measuring equipment.

6. Literature

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