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# Simulation of diesel engine cylinder process using quasi-dimensional numerical model

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ABSTRACT

This paper describes the developed quasi-dimensional numerical model, implemented in the 0D numerical model for direct injection diesel engine simulation. Quasi-dimensional model uses direct solution of equations for cylinder pressure and zone temperatures, without numerical iterations. Numerical model validation has been performed on measured working parameters of the diesel engine with direct fuel injection. After a successful validation, in which simulations have been examined, the movement of various operating parameters in the engine cylinder has been performed. Operating parameters movement for the whole cylinder and the zone without combustion is shown. Except the displayed operating parameters, numerical model monitors thermodynamic processes that occur in spray fuel packages (volumes), from the beginning of the fuel injection into the cylinder, until the opening of the exhaust valves. The developed numerical model goal is to monitor a large part of the engine operating parameters, which have a major impact on the engine working process. Some of them would be difficult or impossible to measure with the existing measuring equipment. Numerical model offers accuracy and precision in the engine operating parameters prognosis. Calculation of single engine process takes less than a minute on a conventional personal computer.

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## 1 Introduction

Quasi-dimensional model development starts from the initial division of the space inside the cylinder into two zones – a zone of combustion products and a fresh mixture zone [1, 2].

Progress in quasi-dimensional modeling occurs at the moment when the cylinder volume division is performed in a manner that during the fuel injection, packages (volumes) that accompany each fuel spray are created and outside the fuel sprays there is a zone without fuel (zone without combustion) [3, 4, 5]. Fuel spray packages are annular in shape, spatial creations and in the spray core they have a form of a truncated cone, Figure 1. As injectors can have a plurality of nozzles, separate volumes are created for each of the fuel sprays, which may be mutually identical or different. The basic assumption of these models states that between fuel spray packages any exchange of mass and energy is not allowed. The only allowed mass exchange is air entrainment from the zone without combustion into spray packages [6].

The division of combustion space into zones enables a more accurate monitoring of temperature distribution. Knowing the exact temperature in certain cylinder zones is essential for the calculation of nitrogen oxide formation. Kinetics of these reactions is very dependent on temperature and requires exact knowledge of temperature fields. While choosing the appropriate model assumptions, it is necessary to be very responsible and aware of the possible consequences. The consequences are reflected not only on emissions, but also on other engine process parameters.

In quasi-dimensional, as well as in the other numerical models, the most difficult task is to properly define pressure and temperature changes that occur in the engine cylinder. The changes of these two values affect every zone in the cylinder space volume, which is not known in advance, and this fact leads to a complex mathematical model. Consequently, a lot of quasi-dimensional models developed so far do not have a direct, but an iterative calculation of these two values.

In this paper, the quasi-dimensional model developed in [7] and implemented in the existing 0D model [8], ac-

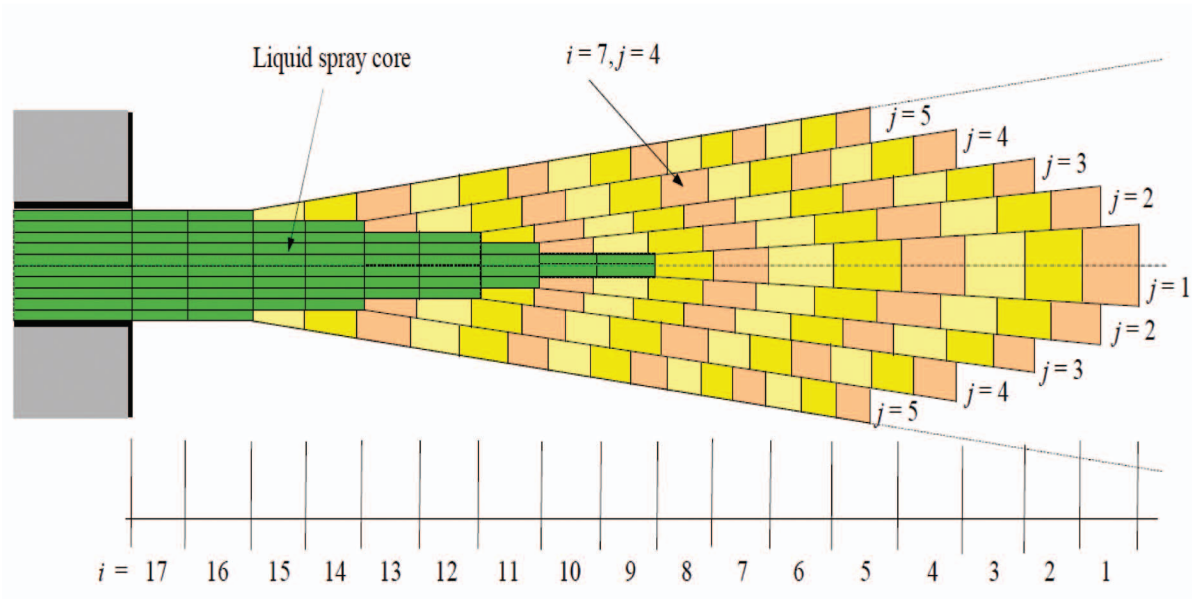


**Figure 1** Fuel spray divided into packages

cording to the model presented in [6], has been used. The numerical model by its specificity and complexity is reflected in the fact that equations were developed for a direct solution of pressure and temperature changes in the cylinder, without the necessity for time consuming numerical iterations. Such a numerical model allows the analysis of all diesel engine process parameters.

With the indexes which are related to each package (*i* = axial index, *j* = radial index), Figure 1, it was necessary to use an additional index *k* for each fuel spray when the fuel sprays are not mutually identical.

## 2 Mathematical model

The mathematical quasi-dimensional model is based on the presumptions of the multizone model [9]. With mathematical excerpt, the following differential equations of pressure and temperature changes in the cylinder have been obtained:

$$\frac{\mathrm{d}T_i}{\mathrm{d}\varphi} = \frac{\frac{1}{m_i}\frac{\mathrm{d}Q_i}{\mathrm{d}\varphi} - K_{3,i}\frac{\mathrm{d}m_i}{\mathrm{d}\varphi} - F_i}{K_{4,i}} - \frac{\frac{E_i}{p}\left[m_i T_i G_i - \left(V_i - m_i T_i \frac{\partial R_i}{\partial p}\right)\frac{\mathrm{d}p}{\mathrm{d}\varphi}\right]}{K_{4,i}}, \quad (1)$$

$$\frac{\mathrm{d}p}{\mathrm{d}\varphi} = \frac{S_1 - p\frac{\mathrm{d}V_c}{\mathrm{d}\varphi}}{\left(V_c - S_2\right)} \quad (2)$$

The variables $E$, $F$, $G$, $K_3$ and $K_4$ in the equation (1) are substitutes for differential expressions, and marks $S_1$, $S_2$ are the replacement for the sums that need to be inserted into the equation for the pressure change (2). Detailed mathematical excerpt are presented in [7]. The index i is an index for any observed volume (for each package of each fuel spray as well as for the zone without combustion).

For the fuel spray packages, it should be noted that all of the displayed equations are related to the thermodynamic volume of the package (volume of gases and vapours). Thermodynamic volume of the package is the geometric package volume reduced for the liquid fuel volume. Fuel vapour in this model is considered as an ideal gas in gaseous mixture with other species.

### Nomenclature

| | |
|---|---|
| $\varphi$ | crank angle (°) |
| $m$ | mass (kg) |
| $p$ | pressure (Pa) |
| $Q$ | amount of heat (J) |
| $R$ | gas constant (J/kg·K) |
| $T$ | temperature (K) |
| $V$ | volume ($m^3$) |
| c | cylinder |
| CA | crank angle |
| ZWC | zone without combustion |

## 3 MAN D 0826 LOH15 diesel engine specifications and measurement results

The test engine has been a high speed diesel engine with direct fuel injection for the freight vehicle drives MAN D 0826 LOH15, Table 1.

**Table 1** Engine specifications

| | |
|---|---|
| Displacement | 6.87 l |
| Number of cylinders | 6 |
| Peak power | 160 kW |
| Cylinder bore | 108 mm |
| Stroke | 125 mm |
| Compression ratio | 18 |
| Crank radius | 62.5 mm |
| Length of the connecting rod | 187.2 mm |
| Length of nozzle bore | 2.3 mm |
| Nozzle diameter | 0.23 mm |
| Number of nozzle holes | 7 |
| Combustion chamber | Bowl in piston |

Several measurement sets have been carried out and for numerical model simulation, the measurement set shown in Table 2 has been chosen.

The parameter for this numerical model calibration is the change of cylinder pressure, as opposed to some other authors who take the rate of heat release as a calibration parameter. The reason for this selection is that the change of cylinder pressure has been obtained experimentally, and the rate of heat release has been calculated from the measured cylinder pressure changes by using the adjusted 0D model which uses the linearized submodel for calculating the properties of the operating substance. Quasi-dimensional model uses a different method for calculating the operating substance properties, which is more accurate and which deviates from the linearized submodel.

Details of the numerical model validation and of the used validation parameters are presented in [7].

## 4 Numerical model results

As a numerical model follows a large number of different engine parameters, in this paper the results of a numerical model for only one operating point, and that is operating point 3, have been shown.

Figure 2 shows the temperature of certain areas in the engine cylinder. The greatest value is the average temperature of fuel spray packages, which is a result of combustion and the most intense heat release. The average cylinder temperature is slightly lower than the fuel spray packages average temperature, which is caused by low temperature in the zone without combustion. This has been expected, because the zone without combustion is a large zone around fuel spray packages where combustion does not occur. The lowest temperature is the average cylinder walls temperature, which is essential for an accurate calculation of heat exchange.

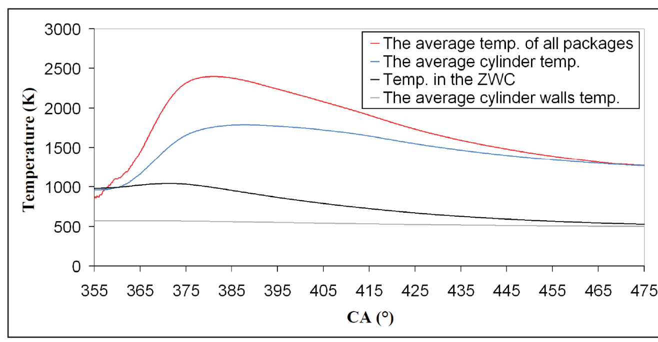


**Figure 2** Temperatures in the engine cylinder

Changes in the total mass of different fuel phases in the cylinder are shown in Figure 3. The mass of the injected fuel increases during the fuel injection process. At the same time, fuel spray packages are formed. When the entire fuel amount per process has been injected, injection stops, and the mass of the injected fuel does not change from that moment. Combusted fuel, observed at the level of the entire cylinder, since the start of the fuel injection has a certain mass. The reason for this is the combusted fuel that remains in the zone without combustion from the previous process, so that, at the time of exhaust valves opening, the mass of the combusted fuel in the entire cylinder is greater than the mass of the injected fuel exactly for the residual mass in the ZWC.

**Table 2** Results of the selected measurement set

| Operating point | Fuel consumption [kg/h] | Air consumption [kg/s] | Rotational speed [$min^{-1}$] | Power [kW] | Soot emission [BSU] | $NO_x$ emission [ppm] |
|---|---|---|---|---|---|---|
| 1 | 9.198 | 0.100764 | 1498 | 43.776 | 0.25 | 870.41 |
| 2 | 13.447 | 0.111920 | 1502 | 67.560 | 0.4 | 1222.91 |
| 3 | 18.040 | 0.126717 | 1502 | 89.319 | 0.55 | 1202.46 |

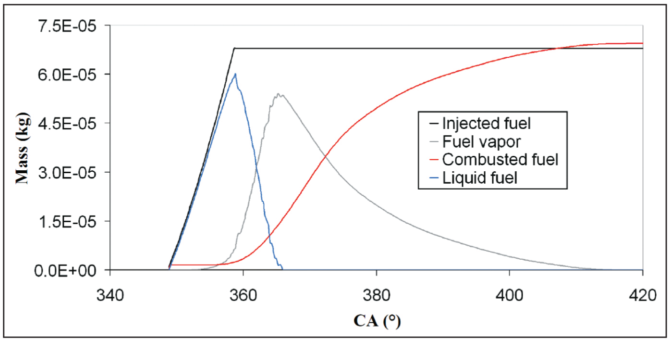


**Figure 3** Changes in the total mass of different fuel phases in the cylinder

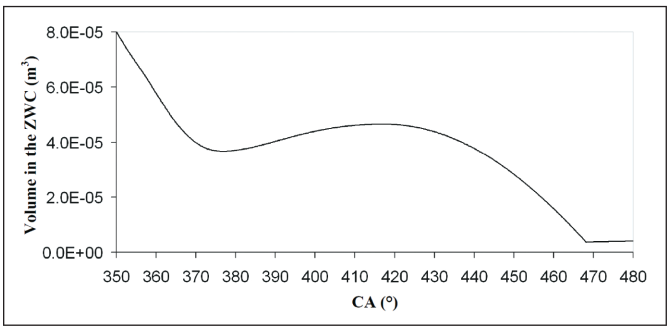


**Figure 4** Volume change in the ZWC

The total volume change in the zone without combustion is presented in Figure 4. At the beginning, the operating media flow from the ZWC into fuel spray packages and the zone without combustion volume reduces proportionally to that flow volume. The flow from the ZWC into fuel spray packages becomes more intense as the packages are progressing through the cylinder, while the cylinder expansion increases the volume of the zone without combustion. The result is that the cylinder expansion has a greater impact on the ZWC volume than the flow into packages, so the overall volume of the zone without combustion increases in that area. At the end of the cylinder expansion, the flow into packages becomes more intensive than the ZWC volume increase by cylinder expansion and the volume of the zone without combustion decreases. The total ZWC volume reduction in this area is also caused by the increasing volume of fuel spray packages, which are becoming bigger and bigger.

Shortly before 470 °CA minimum mass of the ZWC is achieved, and the volume which corresponds to that minimum mass remains constant until the exhaust valves opening. At the time of the exhaust valves opening, the entire cylinder content will be completely mixed and so mixed it will be exhausted out from the cylinder.

Changes of pressure gradient in the cylinder are presented in Figure 5. At the beginning of the fuel injection, pressure gradient shows some fluctuations, which are caused by small packages creation. The basic assumption of this model says that at a certain moment (or crank angle) the pressure field is homogeneous for the entire cylinder.

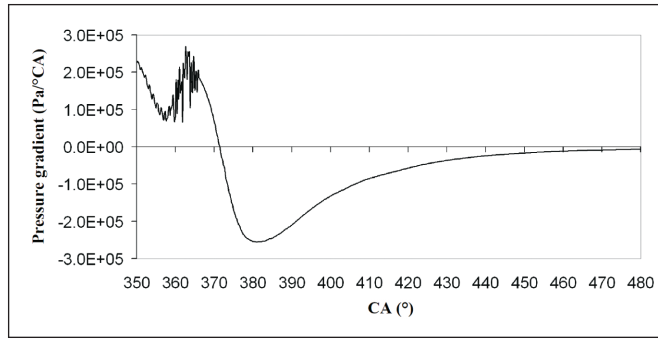


**Figure 5** Changes of pressure gradient in the cylinder

The specific heat at constant volume and pressure in the entire cylinder and in the ZWC show the same trends, as seen in Figure 6. Throughout the cylinder, specific heat rapidly grows during the start of combustion, and after that it is continuously declining until exhaust valves opening. In the zone without combustion the same trend is evident, with the difference in that the initial increase at the beginning of combustion for both specific heats is much lenient when compared to an entire cylinder. This is an expected phenomenon because combustion does not occur in the ZWC volume.

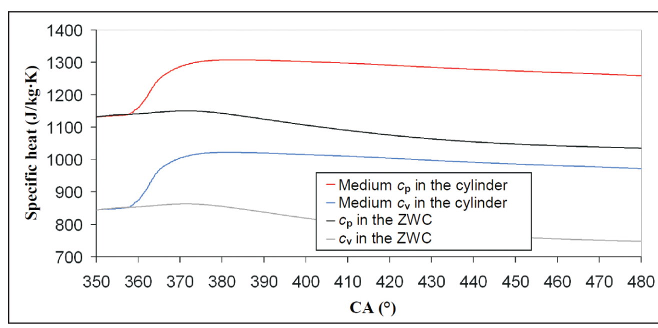


**Figure 6** Specific heat at constant volume and pressure in the cylinder and in the ZWC

Figure 7 and Figure 8 show the change in the total number of moles for various species in the cylinder operating media. In the entire cylinder $H_2O$ and $CO_2$ closely follow each other. Diatomic oxygen $O_2$, observed at the level of the entire cylinder, begins to decrease with fuel vapour combustion. Upon combustion completion, the $O_2$ amount is stabilized and, with that stabilized amount, is ejected out from the cylinder during exhaust, as shown in Figure 8. The increased OH emission is evident at the start of combustion, and in the middle of combustion it reaches its maximum, Figure 7. During expansion, the OH emission is reduced, and appears on exhaust with a very low amount.

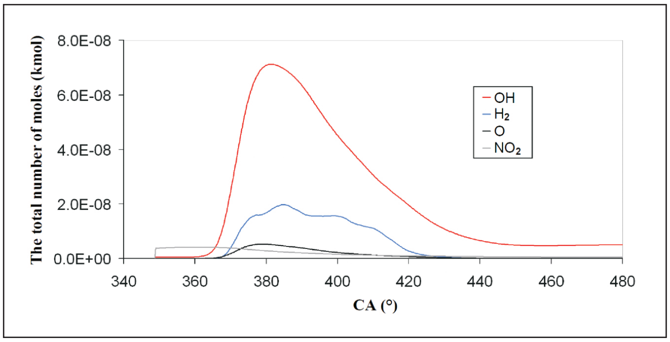


**Figure 7** Total number of moles for OH, $H_2$, O and $NO_2$ in the cylinder

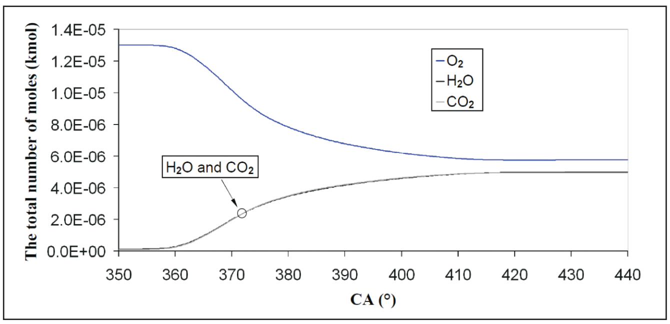


**Figure 8** Total number of moles for $O_2$, $H_2O$ and $CO_2$ in the cylinder

## 5 Conclusions

This paper presents a developed quasi-dimensional model implemented in the 0D model with direct calculation of temperature and pressure in the internal combustion diesel engine cylinder.

Quasi-dimensional model global results for the entire cylinder and for the zone without combustion are presented. The model also calculates the operating parameters in each fuel spray package (volume), in order to predict the total emissions from the engine.

It is necessary to emphasize the importance of accurate operating media properties calculation in order to obtain precise simulation results. The sub-model for the calculation operating media properties is completely autonomously developed for quasi-dimensional model needs, and gives accurate predictions comparable with similar, separately developed programmes.

A large number of parameters monitored with the quasi-dimensional model have been the reason that the paper has presented the simulation results for only one operating point, with remarks that the model was also tested for other operating points and in them all it has shown acceptable deviations. Measuring some of the presented simulation results would be very difficult on the real engine, even with the highest quality measuring equipment.

This numerical model achieved the desired goal: to monitor different engine operating parameters by using the numerical simulations with equal or smaller deviations in comparison to other quasi-dimensional or CFD models in the available literature.

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