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Volume agglomeration process in quasi-dimensional direct injection diesel engine numerical model

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ABSTRACT

This paper describes the quasi-dimensional numerical model for direct injection diesel engine, implemented in previously developed 0D model. The presented model uses a direct solution of equations for cylinder pressure and zone temperatures. A process of control volumes agglomeration from a set of the small fuel spray packages (control volumes) into one of the large ones is presented in details. This process contributes to fast simulation performances and to the numerical code stability. Numerical model validation was performed in three randomly selected engine operating points. Presented model results show a wide range of operating parameters which can be traced in detail, during the whole engine working process. Direct solution of temperature and pressure changes, in conjunction with the fuel spray packages agglomeration, presents a contribution to the quasi-dimensional engine process modeling.

1. Introduction

Quasi-dimensional models represent a compromise between 0D and CFD models for internal combustion engine simulations. 0D numerical models assume a homogeneous mixture of gases in the cylinder as a whole and they have no possibilities in predicting engine emissions (NO_x, CH_x and particles) [1–3]. The speed and intensity of chemical reactions, same as for those responsible for pollutant formation, are highly sensitive to local temperature field and local species concentrations. The same reactions have different intensity at the medium in-cylinder temperature and species concentration, so the results can be completely erroneous one in the case of the 0D model. CFD models enable the most detailed simulations, but these simulations have an extremely long time of calculation [4], and they are not accessible for the whole engine simulations.

As a compromise between 0D and CFD modeling, the development of quasi-dimensional models started with the initial division of the space inside the cylinder into two or more zones - one or more zones for spray packages and one fresh mixture zone [5,6]. This kind of models enables a rude prediction in the engine emissions, but not in detail.

Quasi-dimensional modeling occurs at the start of fuel injection. Injected fuel spray is divided in spray packages (volumes) and new spray packages are added as injection continues. Such set of spray packages accompany each fuel spray, Fig. 1. Outside the fuel sprays is a one large zone without fuel (zone of fresh air without combustion) [7–9]. Fuel spray packages are annular in shape, spatial creations and in the spray core they have a form of a truncated cone. As injectors can have more, mutually different nozzles, separate volumes are created for each of the fuel sprays.

The basic assumption of these model states that between spray packages it is not allowed any mutual exchange of mass or energy. The only allowed mass exchange is the air entrainment from the zone without combustion (ZWC) into spray packages [10], when the necessary conditions are fulfilled in each spray package.

According to Fig. 1, with the indexes which are related to each package, (i = axial index, j = radial index), it was necessary to use an additional index k for each fuel spray when the fuel sprays are mutually different. In the case that fuel sprays are mutually equal, only one spray is calculated, and the results are transferred to the rest of similar fuel sprays.

In this paper, it is applied the quasi-dimensional model developed in Ref. [11] and implemented in the already existing 0D

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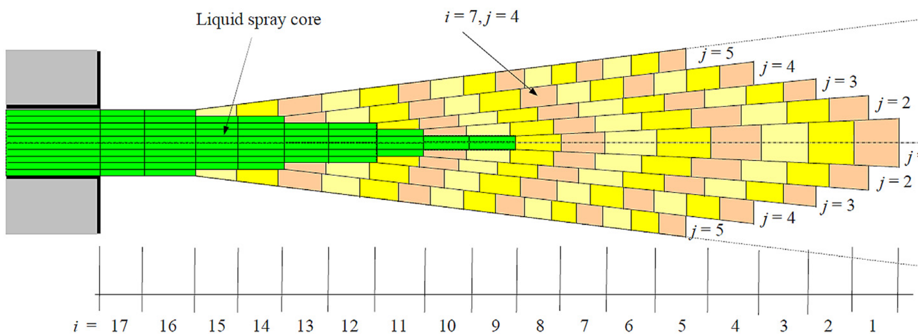

Fig. 1. Fuel spray divided into packages (control volumes).

model [1], according to the model presented in Refs. [8] and [9]. Developed quasi-dimensional model is based on a number of equations and conclusions from Refs. [12] and [13]. The contraction of fuel flow in the nozzle was modeled by using equations from paper [14]. Selected diesel fuel was $C_{14}H_{30}$. Liquid spray decomposition and calculation of droplets number and diameter was performed according to the paper [15]. Fuel evaporation was modeled by using equations from Refs. [16–19]. Liquid fuel energy conservation equation was used to monitor the liquid fuel temperature, which is a basic parameter for the fuel evaporation calculation. Fuel vapour in this model is considered as an ideal gas in the gaseous mixture with other species. Ignition delay is formulated using constants and equations from paper [20]. Finally, the combustion is modeled according to Yoshizaki [7] model.

2. Numerical model for temperature and pressure changes

Numerical model equations were developed for a direct solution of pressure and temperature changes in the cylinder, without the necessity for time consuming numerical iterations. With mathematical excerpt, (details are presented in Ref. [11]), the following differential equations were obtained:

$$A_z = 1 + \frac{T_z}{R_z}\frac{\partial R_z}{\partial T_z}, \tag{1}$$

$$B_z = 1 - \frac{p}{R_z}\frac{\partial R_z}{\partial p}, \tag{2}$$

$$C_z = \left(\frac{\partial u_z}{\partial p}\frac{p}{B_z}\frac{A_z}{T_z} + \frac{\partial u_z}{\partial T_z}\right), \tag{3}$$

$$D_z = \left(\frac{u_z}{m_z} + \frac{1}{m_z}\frac{\partial u_z}{\partial p}\frac{p}{B_z}\right), \tag{4}$$

$$E_z = \left(\frac{p}{m_z} - \frac{1}{V_z}\frac{\partial u_z}{\partial p}\frac{p}{B_z}\right), \tag{5}$$

$$F_z = \left[\frac{1}{R_z}\frac{\partial u_z}{\partial p}\frac{p}{B_z}G_z + \left(\frac{\partial u_z}{\partial \lambda_z}\frac{d\lambda_z}{d\varphi} + \frac{\partial u_z}{\partial Y_{vap,z}}\frac{dY_{vap,z}}{d\varphi}\right)\right], \tag{6}$$

$$G_z = \left(\frac{\partial R_z}{\partial \lambda_z}\frac{d\lambda_z}{d\varphi} + \frac{\partial R_z}{\partial Y_{vap,z}}\frac{dY_{vap,z}}{d\varphi}\right), \tag{7}$$

$$H_z = \frac{C_z}{\left(R_z + T_z\frac{\partial R_z}{\partial T_z}\right)}, \tag{8}$$

$$K_{1,z} = \frac{B_z u_z T_z\frac{\partial R_z}{\partial T_z} + p u_z\left(\frac{p}{R_z} - 1\right)\frac{\partial R_z}{\partial p}}{A_z B_z m_z R_z}, \tag{9}$$

$$K_{2,z} = \frac{1}{m_z R_z A_z}\frac{\partial u_z}{\partial T_z}, \tag{10}$$

$$K_{3,z} = \frac{(u_z + R_z T_z)}{m_z} = \frac{h_z}{m_z}, \tag{11}$$

$$K_{4,z} = \frac{\partial u_z}{\partial T_z} + R_z A_z, \tag{12}$$

$$S_1 = \sum_z \left[\frac{\frac{1}{m_z}\frac{dQ_z}{d\varphi} - K_{1,z}\frac{dm_z}{d\varphi} + H_z T_z G_z - F_z}{K_{2,z}}\right], \tag{13}$$

$$S_2 = \sum_z \left(m_z T_z\frac{\partial R_z}{\partial p} + \frac{\frac{E_z}{p}\left(V_z - m_z T_z\frac{\partial R_z}{\partial p}\right)}{K_{2,z}}\right), \tag{14}$$

$$\frac{dT_z}{d\varphi} = \frac{\frac{1}{m_z}\frac{dQ_z}{d\varphi} - K_{3,z}\frac{dm_z}{d\varphi} - F_z - \frac{E_z}{p}\left[m_z T_z G_z - \left(V_z - m_z T_z\frac{\partial R_z}{\partial p}\right)\frac{dp}{d\varphi}\right]}{K_{4,z}}, \tag{15}$$

$$\frac{dp}{d\varphi} = \frac{S_1 - p\frac{dV_c}{d\varphi}}{(V_c - S_2)}. \tag{16}$$

The variables $A, B, C, D, E, F, G, H, K_1, K_2, K_3$ and K_4 in the equations from (1) to (12) are substitutes for differential expressions that need to be inserted into the equation for the control volume temperature change (15), and marks S_1, S_2 are the replacement for the sums that need to be inserted into the equation for the pressure change (16). The index z is an index for any observed volume (for each package of each fuel spray as well as for the zone without combustion). Numerical model takes into account the assumption that the pressure is equal in whole cylinder space in the observed moment. This set of equations enables the direct solution for pressure and temperature changes for control volumes. From the mass, temperature and pressure the volume is obtained from the