Model of fuel spray propagation in direct injecting internal combustion engines under cross-flow conditions

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Abstract. This paper is devoted to modelling of the fuel spray propagation into a cylinder of direct injecting internal combustion engines. A number of experiments were carried out to obtain data for the calculation of velocity profiles inside the spray, as well as its trajectory under cross-flow conditions. A one-hole injector was used in the experiments. The injection pressure varied from 100 till 150 bar and the air cross-flow velocities ranged from 0 till 50 m/s. The semi-empirical model was developed to describe the fuel spray propagation. The results obtained from the model and experiments were compared. The agreement of the results from experiments and the model for low velocities of the cross-flow (0-25 m/s) is significant. However, for high velocities of the cross-flow (30-50 m/s) the agreement is low. Thus, in this paper the improved model of the fuel spray propagation is proposed. A new model is based on splitting spray into parts with different densities. Each part moves with its own velocity and along its own trajectory.

1. Introduction

According to the data of the International Energy Agency the dynamics of the global car production, as well as the consumption of gasoline and diesel fuel, has been growing every year. The emission legislation requirements become higher and new emission standards appear. The amount of harmful substances in exhaust gases does not depend only on the level of direct purification by means of filters. It is highly determined at the phase of the fuel-air mixture formation in a combustion chamber [1-2]. Thus, investigation and analysis of the fuel-air mixture formation in the combustion chamber of widely applied direct injection engines are significant points of interest.

Direct injection engines have to face and satisfy constantly growing emission standards. Theoretical fuel saving for gasoline direct injection engines is up to 60% in the idle regime, up to 35% in low and middle loaded regimes and up to 6% in full load regimes [3]. The fuel saving may be reached in three main aspects. The first is running the engine in the regime of stratified mixture formation. The fuel-air mixture concentration which is necessary for ignition should be achieved only very close to a spark plug. At that the extremely lean mixture should exist in the rest of the volume of a combustion chamber. In addition to fuel saving, this regime allows reducing heat losses from the cylinder walls. The second component is a direct injection engine design without a throttle blade to
reduce energy losses. The third way is to increase the compression ratio in the cylinder that provides a smaller engine with the same power output and reduces heat losses.

An investigation of fuel-air mixture formation is very important to achieve all benefits of direct injection technology. Studies of velocity, concentration, temperature and pressure fields in a combustion chamber are extremely important. The determining flow affecting the mixture formation in a combustion chamber is an air flow coming from the intake valve with an angle of 90° relative to an injected fuel jet. This is why such flow is named cross-flow. Such flows were also investigated in [4-6]. However, currently available data of the theory of turbulent jets and experimental research do not allow fully simulating the process of mixture formation in a combustion chamber. Thus, the development of semi-empirical models for an accurate description and prediction of the spray propagation under cross-flow conditions is essential.

2. Experiments and semi-empirical model

The experiments in fuel spray propagation under cross-flow conditions as well as the developed semi-empirical model were described in details in papers [7,8]. So this paper will only provide a short description and principle results obtained as a result of experiments and modelling.

The experiments took place at the laboratory of the Engineering Thermodynamics Institute at Friedrich-Alexander University in Erlangen, Germany. The main parts of the experimental set up are as follows: the air fan forcing the air through the chamber, where the injection takes place; the injection channel with cross-section of 7x7 cm; one-hole injector, installed vertically at an angle of 30º to obtain a vertically directed jet; and the high-speed camera (20000 pictures per second). The experimental settings are presented in table 1. The optical visualization by Shadowgraph technique [9] was applied for obtaining pictures of the spray. The spray pictures obtained by the authors during the experiments are given in figure 1 and figure 2.

In addition, measurements of air-flow velocities in the injection channel were carried out using the following equipment: hot-wire anemometer TESTO 425 and hot-wire anemometer with Pitot tube TRONEC TA400. These data were subsequently used to build velocity profiles in the channel.

Table 1. Experimental settings.

| Parameter                  | Value               |
|----------------------------|---------------------|
| Injection pressure, bar    | 100, 150, 170       |
| Ambient pressure, bar      | 1                   |
| Fuel                       | Isooctane           |
| Cross-flow velocity, ms⁻¹  | 0, 5, 15, 25, 30, 40, 50 |
| Nozzle diameter, m         | 10⁻⁴                |

The present model describing fuel spray propagation under cross-flow conditions was based on the models of gas jet blowing-off by a gas flow proposed in [10]. The authors considered the displacement of the selected spray volume moving with average velocity separately along the vertical and horizontal axes. To calculate the spray displacement along each axis, the impulse conservation law was applied. The investigated spray was biphasic. Eventually, the cone angle was equal to 6° and was taken from the experiment without the cross-flow. The cone angle is a variable parameter of the model. According to the results of the model, the following data were obtained: velocity profiles of the cross-flow in the injection channel; the average density of the selected spray volume; and vertical, horizontal and resulting spray displacement. The spray displacement according to the results of the experiments and the model for different cross-flow velocities is presented in figure 1 and 2.

The proposed model shows a good agreement with the experimental data at low cross-flow velocities (5-25 ms⁻¹). However, at high velocities (30-50 ms⁻¹) the agreement is low (figure 3 and 4).
Figure 1. Spray propagation with cross-flow velocities of 0, 5, 15, 25 ms⁻¹ [7].

Figure 2. Spray propagation with cross-flow velocities of 30, 40, 50 ms⁻¹ [7].

Figure 3. Comparison of the spray displacement according to experiments and the model for low cross-flow velocities.
Figure 4. Comparison of the spray displacement according to experiments and the model for high cross-flow velocities.

3. Results and discussion
The proposed earlier model operates with the average velocity of fuel particles in each selected spray volume (figure 5). However, it is known, that the real velocity profile follows the normal Gauss distribution law. Therefore, the authors propose an improved model (figure 6) where the fuel spray propagation is described by the propagation of two (or more) selected spray volumes. Each volume moves independently, along its own trajectory and with its own velocity. Figures 5 and 6 were obtained for the spray without cross-flow.

Figure 5. Earlier proposed model with average velocity of fuel particles.

Figure 6. An improved model with movement of two selected volumes.

The improved model is physically logical. The first volume V1 will have a large density and vertical velocity component. Thus, it will have a larger vertical displacement (figure 7a). The second volume V2 will have a smaller density and larger horizontal velocity component. Thus, it will have a larger horizontal displacement (figure 7a).
The splitting of the selected spray volume $V$ into two $V_1$ and $V_2$ was carried out by solving the following system of equations:

$$
\begin{align*}
V &= V_1 + V_2 = \int_{0}^{V_{\text{Gauss}}} C \cdot e^{-\sigma \cdot x^2} \, dx \\
\sum_{i=1}^{n} (y_i - C \cdot e^{-\sigma \cdot x_i^2})^2 &\rightarrow \min
\end{align*}
$$

(1)

$V_1, V_2$ are the volumes of the first and second selected volumes (figure 6); $C, \sigma$ are the variables to adjust the height and the width of the Gauss curve which are equal to maximum spray velocity and spray diameter in any spray cross section, respectively; $V_{\text{Gauss}}$ is the volume of the body under Gauss function $f(x) = C \cdot e^{-\sigma \cdot x^2} \, dx$ which rotates around Y-axis; $V$ is the volume of the selected volume from the previous model described in [7]. The second equation in the system (1) applies the least-squares deviation method for finding the unknown coordinates of the points $1\{C, y\}$, $2\{x, y\}$, $3\{\sigma, y\}$, where $n$ is the the amount of the points (figure 6). Points should be maximally close to Gauss curve. As the height and the width are known from the previous model [7] there are only two unknown variables $x, y$ in the system [1].

![Figure 7](image_url)

**Figure 7.** The scheme of the selected volumes movement according to the previous (a) and improved (b) model.

Spray velocity profiles at different distance from the nozzle without cross-flow have been obtained according to the improved model (figure 8). The obtained figures show that the spray expands as it moves further from the nozzle, and its density and velocity decrease, which corresponds to the physical laws of the turbulent sprays motion.

The standard deviation of the functions $V$, $V_1$ and $V_2$ from Gauss function $V_{\text{Gauss}}$ has been calculated (figure 5 and 6). Table 2 shows that the standard deviations for the improved model are more than 3 times less than for the previous model.

Table 2. Standard deviations for the models.

| Distance from the nozzle, mm | Standard deviations for the previous model *10^5 | Standard deviations for the improved model *10^5 |
|-----------------------------|-----------------------------------------------|-----------------------------------------------|
| 15                          | 18.74                                        | 5.58                                         |
| 35                          | 17.96                                        | 5.18                                         |
| 70                          | 10.86                                        | 3.17                                         |

4. Conclusions

The semi-empirical model has been developed to describe the fuel spray propagation under cross-flow conditions which is in good agreement with experimental data at low cross-flow velocities of 5-
25 ms\(^{-1}\). The results of the model for spray propagation under high speed cross-flow conditions of 30-50 ms\(^{-1}\) significantly deviate from the experiment;

The improved semi-empirical model has been developed. According to preliminary results, the use of the improved model will significantly enhance the description of the experimental data.

![Figure 8. Velocity profiles inside the spray without the cross-flow at different distance from the nozzle.](image)

### References

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