**Ivan Filipović, Boran Pikula, Dževad Bibić**

ISSN 0350-350X
GOMABN 50, 3, 215-232
Izvorni znanstveni rad / Original scientific paper
UDK 621.436.013.4.038.5.001.572.001.575 : 532.525 : 516.3

# INFLUENCE OF INJECTOR ON CHARACTERISTICS OF FUEL DISPERSION IN DIESEL ENGINE

*Abstract*

*The combustion process in the IC engines predominantly depends on the air/fuel mixture preparation and conditions for its preparation. The process of air and fuel mixing can be analyzed through energy introduced with air and fuel in relation with necessary energy for rational formation of air/fuel mixture. The main role for the quality of the air/fuel mixture in diesel engines has energy introduced by the fuel, i.e. the characteristics of fuel injection process. These characteristics are mostly represented by: jet length, cone jet angle, physical and chemical structure of jet on different cross sections. The physical jet structure is generally described by average Sauter diameter of droplets. The approaches to calculate these parameters are as follows:*

- *modeling and calculating by a numerical method in order to solve 2D and 3D models, depending on the ambient conditions,*
- *using different semi-empirical models for calculatons of mentioned parameters.*

*Each approach the fuel jet characteristics calculations requires knowledge of so-called "boundary and initial" conditions, which are defined by the exit of fuel flow from nozzle orifice. In this paper using an example of jet fuel length it will be explained the current way of taking the boundary conditions at the nozzle, the role of injector itself in this specific case, as well as a new approach in defining the boundary conditions.*

## 1. Introduction

The combustion process in the IC engines, with direct fuel injection in the engine cylinder depends on how the air and fuel mixture is made. The process of air and fuel mixing can be studied through the energy brought into the engine via fuel and the air. By diesel engines, especially those with bigger swept volume, the main role in the process of air and fuel mixing has the energy introduced via fuel. Within the real conditions manifestation of the energy introduced via fuel is reflected through the jet characteristics of sprayed fuel. Within the real conditions manifestation of the energy introduced via fuel is reflected through the jet characteristics of sprayed fuel.

The fuel jet characteristics, regarding surrounding conditions of the jet development, can be expressed in forms of:

- jet dimensions (jet length ($X_m$), cone jet angle ($2\theta$), jet dimensions after hitting the hard obstacle ($Y_m$, $h_m$), etc.),
- physical and chemical structure of fuel jet where physical jet structure is usually described by average Sauter diameter ($d_{32}$) of fuel droplets.
  The chemical structure depends on fuel content in the surrounding conditions and there is no evaluation criteria for it.

In the process of air/fuel mixture the characteristics (dimensions) of fuel jet form are observed based on which conclusions are brought on homogeneity in the whole combustion area, overlapping with the nearby jets, the influence of boundary walls of the combustion area, etc. This is the way most authors analyze the form of fuel jets under different conditions and determine the factors influencing the dimensions of fuel jet. In the process of jet characteristics analysis most commonly found forms are shown in the Figure 1; where in the Figure 1a) is shown the jet form in an uninterrupted surrounding without limits.

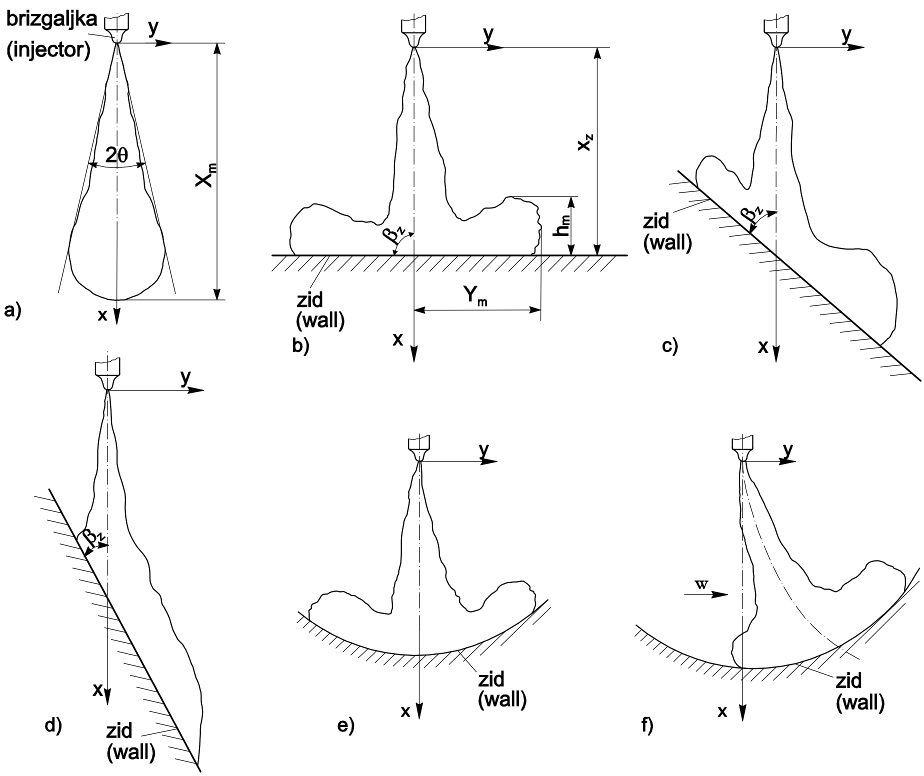


Figure 1: Typical fuel jet forms in different environmental conditions

The Figures 1 b), c), and d) show the jet forms in the uninterrupted surrounding, when hitting the flat wall at the distance of XZ, at the angle of βz, while in the Figures 1 e) and f) jets are hitting the curved wall in the uninterrupted surrounding (Figure 1 e)) and the surrounding with a air flow rate *w* (Figure 1 f)). These are some of the typical examples which can be used for the analysis of injection quality. Apart from variation of the surrounding pressures and temperature, the real conditions of IC engine performance also include different kinds of air flow (turbulent, transversal, linear) as well as a variable space limit.Within these conditions jet analyses become far more complicated and are rarely found in the relevant literature. The typical values mostly found in the analyses are [1], [2], [3]:

- jet length ($X_m$),
- jet dimensions after hitting the wall ($Y_m$, $h_m$) and
- cone jet angle (2θ).

By using the example of a jet length in the function of time of injection ($X_m$=f($t$)), the influence of constructive characteristics of injector and hydrodynamic characteristics of fuel in the injector is presented.

## 2. The analysis of fuel jet characteristics

The common methods of defining and analyzing the characteristics of fuel jets:

- experimental,
- calculated, the use of complex 2D and 3D models,
- calculated, the use of correlation (semi-empiric) expressions.

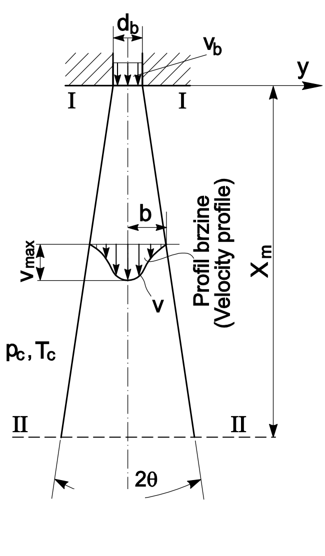


Figure 2: Physical model of the free jet

The latter method of defining of the fuel jet characteristics is usually mentioned in the referent literature. While studying other authors' work a great number of semi-empiric expressions for calculation of characteristics $X_m$, $Y_m$, $h_m$, 2θ and $d_{32}$ can be found. The typical values $X_m$, $Y_m$ and $h_m$, primarily the jet length ($X_m$) have the same form of semi-empiric expression with different constant values, by almost all the authors.

All the authors ([1], [3] and [4]) start with the well known physical model for jet length shown in the Figure 2 and they all use the mathematical model for the so-called stationary jets, whereas can be conidered to have a constant jet momentum ($K$) at reasonably short jet lengths. In a mathematical form it can be presented as the equality of momentum in the section I-I and II-II (Figure 2), which means:

$$K_{I-I} = K_{II-II} \tag{1}$$

There is a presumption that the velocity profile in the jet, outside of potential jet centre, is the function $v = v_{\max} f(\eta)$, where $\eta = y/b$, and the function f matches the best with the Gaussian error function. The value of momentum in the section I-I can be described as:

$$K_{I-I} = \rho_L \frac{d_b^2 \pi}{4} v_b^2 = \frac{\pi}{2} C_b^2 d_b^2 \Delta p \tag{2}$$

where the velocity of fuel at the injector inlet ($v_b$) is calculated through the Bernoulli equation for the relevant positions, the injector inlet and outlet, as:

$$v_b = C_b \sqrt{2\Delta p / \rho_L} \tag{3}$$

where: $\Delta p$ - pressure drop from the injector inlet to the jet outlet ($\Delta p = p_A - p_C$, Figure 3 a)),

$\rho_L$ - fuel density,

$C_b$ - coefficient taking all the losses in the injector,

$p_c$ – environmental pressure.

The momentum for the section II-II can be written as:

$$K_{II-II} = \int_o^b \rho_m v^2 2\pi y dy = 2\pi \rho_c v_{\max}^2 b^2 \varphi_1 \tag{4}$$

with $\varphi_1 = \int_o^1 f^2(\eta) \eta d\eta$,

$\rho_c = p_c / (RT_c)$ surrounding density,

$T_c$ – surrounding temperature,

$R$ – gas constant.

Taking that the width *b* is proportional to the jet length ($b = C_1 X_m$), density in the jet ($\rho_m$) approximately equal to the density of the environment ($\rho_c$) tj. $\rho_m \approx \rho_c$, as well as the fact that the maximum velocity $v_{max}$ can be expressed as $v_{\max} = dX_m / dt$, finally, based on the expressions (1), (2) and (4) expression for the jet length can be writen as:

$$X_m = C d_b^{0,5} \left( \frac{\Delta p}{\rho_c} \right)^{0,25} t^{0,5} \tag{5}$$

where the constant *C* is expressed as:

$$C = \left( C_b C_1^{-1} \varphi_1^{-0,5} \right)^{0,5} \tag{6}$$

The majority of authors who have developed the correlation expressions for the jet length ($X_m$) began with the expression (5), which works in the jet length zone, outside of potential jet centre, i.e. outside of the zone of uninterrupted fuel jet. The expression (5) is often used in the referent literature where:

the constant *C* varies between 3,01 and 3,9 ([5],[6] and [7]) and

the pressure drop $\Delta p$ is considered to be a constant value.

Jet length ($X_m$) also has a significant influence on the jet dimensions after hitting the wall. For example, the values $Y_m$ and $h_m$ (Figure 1) can be expressed through the correlation expression:

$$Y_m = C_2 \Delta p^{0,89} \rho_c^{-0,24} \left( t - t_z \right)^{0,48} \tag{7}$$

$$h_m = C_3 \Delta p^{0,52} \rho_c^{0,048} \left( t - t_z \right)^{0,35} \tag{8}$$

There is a pressure drop along the injector ($\Delta p$) as well as the constant $C_2$ and $C_3$ which are also influenced by flow resistance (loss coefficient) $C_b$ in the injector. The value $t_z$ represents the time of the contact between the fuel jet and the wall. Due to the similar influence of thepressure drop $\Delta p$ and loss coefficient in the injector $C_b$, more attention will be paid to the fuel jet length $X_m$ and furthermore, it will be used for the analysis of influence of injector construction on the characteristics of spray fuel jet.

Since the fuel injection is a non-stationary process and the pressure drop is variable within one injection cycle, most authors define the value $\Delta p$ with the mean pressure during the fuel injection process or average injection pressure in the first 0,5 ms of the injection process [8]. Regarding all these dilemmas and the fact that the constant *C* dissipates more than 30 %, it is necessary to pay more attention to the influence of the injection system and the injector itself on the selection the constant *C*.

## 3. Research results on the specific injector

In the analysis we used the specific Bosch injector, type DLL 25S834 containing one jet with a diameter $d_b$ = 0,68 mm and jet length $l_b$ = 2 mm. The injector appearance is given in the Figure 3 a), while in the Figure 3 b) there is its physical model.

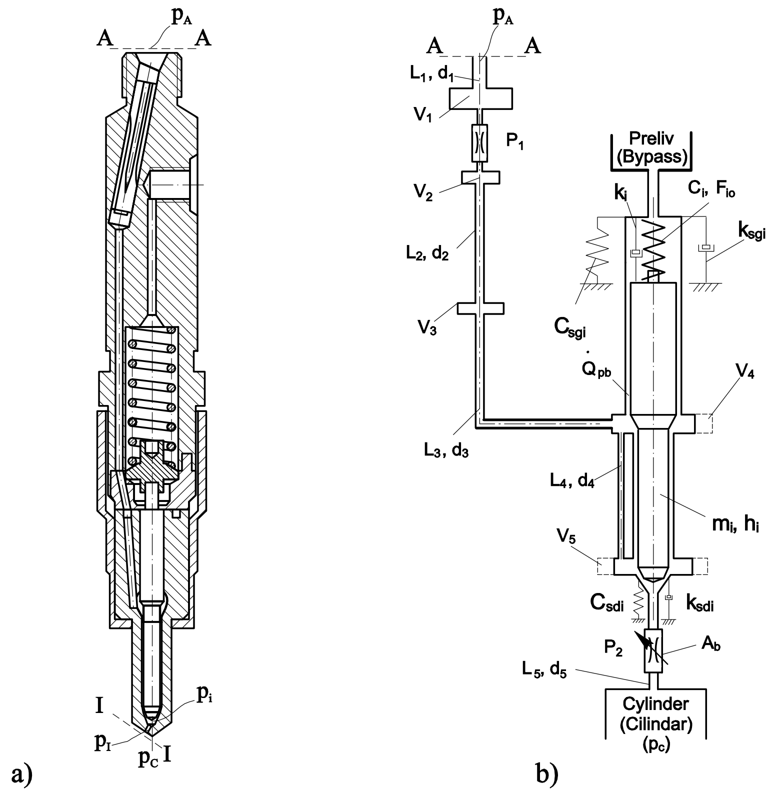


Figure 3: Realistic scheme of injector a) and physical model b)

The calculation of the characteristics of fuel jet length with all the semi-empiric expressions is based on the difference between pressures $\Delta p = p_A - p_C$, since the pressure $p_A$ can be easily measured. Nevertheless, when it comes to calculating of fuel flow rate at the injector outlet ($v_b$) energy losses in the injector need to be predicted that can not be unambiguously determined. This can be seen from the Bernoulli equation for the sections A-A and I-I (Figure 3 a)):

$$p_A + \frac{\rho_L v_A^2}{2} = p_C + \frac{\rho_L v_b^2}{2} + \sum_i \xi_i \frac{\rho_L v_i^2}{2} + \sum_j \lambda_j \frac{l_j}{d_j} \frac{\rho_L v_j^2}{2} \quad , \tag{9}$$

that can be used for the fuel flow rate at the injector outlet $v_b$ calculations (3) with all the losses (linear and local) expressed through the loss coefficient $C_b$. From the expressions (9) and (3) it can be seen that the value of $C_b$ coefficient depends on constructive characteristics of the injector and hydrodynamic flow conditions in the injector. This coefficient, apart from not being constant, can not be unambiguously calculated without serious modeling of the hydrodynamic processes in the injector. For the specific injector in the Figure 3 a) a physical model shown in the Figure 3 b) was made providing the analysis and the calculation of the characteristics of fuel flow along the injector as well as the calculation of kinematic characteristics of injector needle. A combined multi-dimensional and one-dimensional mathematical model were used along with equations of continuity and momentum. The Newton's second law was used in defining the injector needle lift. The model is precisely described in [2], and this paper only presents some results of pressure change at the injector inlet ($p_A$), the pressure under the centre of injector needle ($p_i$) and the pressure at the end of injector jet ($p_I$) in the Figure 4, for two typical angular speeds of high pressure pumps ($n$ = 1100 min$^{-1}$ and $n$ = 700 min$^{-1}$).

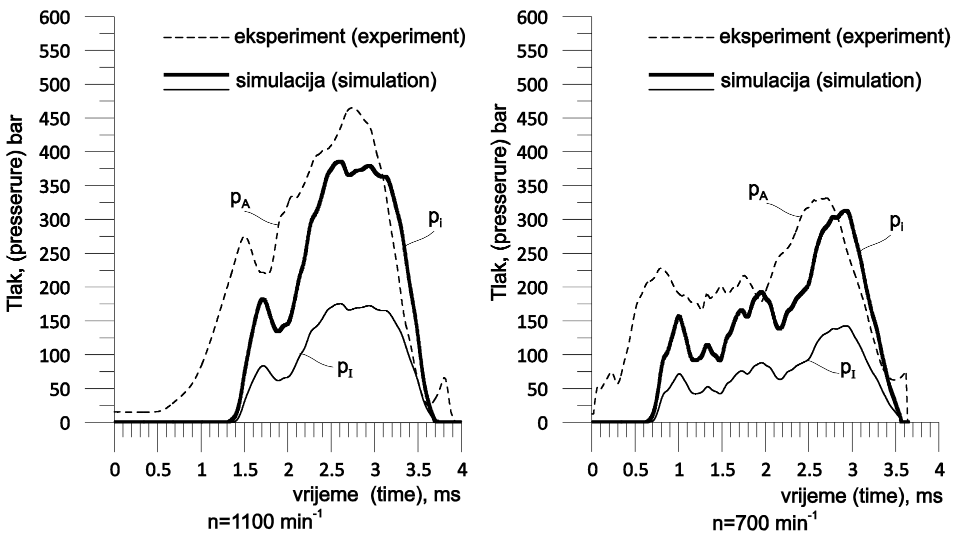


Figure 4: Change of pressure at characteristic positions of the injector for two speed regimes of high pressure pump

By knowing the pressure $p_I$ (outlet of injector jet), instead of the pressure $p_A$ at the injector inlet the expression (3) becomes more simplified: $v_b = \sqrt{2(p_I - p_C)/\rho_L}$ and the expression (6) for the constant $C$ becomes:

$$C^* = \left(C_1^{-1}\varphi^{-0,5}\right)^{0,5} \tag{10}$$

Knowing the character of the values $C_1$ and $\varphi_1$, which are for the appropriate surrounding conditions ($p_C$, $T_C$) practically constant values, the value $C^*$ becomes constant and it does not depend on constructive injector characteristics and hydrodynamic characteristics of fuel flow in the injector.

## 4. Conclusion

Based on the information considering the calculation of the characteristics of spray fuel jet, the influence of constructive and hydrodynamic characteristics of the injector has been clearly emphasized. Due to different constructive characteristics of the injector as well different characteristics of pressure and fuel flow rate in the injector, up to now the correlation expressions on the jet length ($X_m$) found in the relevant literature have not explicitly expressed the influence of the injector, except from the jet diameter. Due to losses in the injector ($C_b$), the value of the constant ($C$) (6) displays significant dissipation according to different authors.

By offering the model for the calculation of velocity ($v_b$) and pressure ($p_l$) at the outletof the injector these kinds of problems can be avoided, and a new constant in the correlation expressions ($C^*$) also presents the substantial constant no matter what kind of an injector is used and what are the flow losses in the injector and in the whole injection system.

### Reference

1. Filipović I., Bibić Dž., Pikula B.: Sistemi za dobavu goriva kod dizel motora, Mašinski fakultet Sarajevo, Sarajevo, 2010.
2. Pikula B.: Istraživanje karakteristika sistema za ubrizgavanje pri upotrebi dizela, biodizela i njihovih mješavina u različitim eksploatacionim uslovima, disertation, Mašinski fakultet Sarajevo, Sarajevo, 2007.
3. Yule A. J., Mirza M. R., Filipović I.: Correlations for Diesel Spray Penetration Including the Effects of the Break-up Zone, 5th International Conference on Liquid Atomization and Spray Systems (ICLASS 91), Gaithersberg, MD, 1991, USA.
4. Idoum A., Packer J. P., Wallace F. J., Charltom S. J.: An Experimental and Analytical Study of Jet Impingement and Wall Jets in High Swirl D.I. Diesel Engines using the Hydraulic Analogy, SAE 850263, 1985.
5. Dent J. C.: A Basis for the Comparison of Various Experimental Methods for Studying Penetration, SAE Trans, vol. 80, Paper No 710571, 1971.
6. Pischinger F.: Verfahren zur Untersuchung von Diesel-Einspritzstrahlen, MaschBau Warmew, 10, 1955.
7. Arai M., Tabata M., Hiroyasu H.: Disintegrating Process and Spray Characterization of Fuel Jet Injected by a Diesel Nozzle, SAE 840275, 1984.
8. Filipović I., Gebert K., Černej A., Lasić D., Dobovišek Ž.: Utjecaj pritiska ubrizgavanja na proces dezintegracije mlaza goriva, Goriva i maziva, 1-2, 1992.

| UDK | kjučne riječi | key words |
|---|---|---|
| 621.436.013.4 | dizelov motor, ubrizgavanje i raspršivanje goriva | diesel engine, fuel injection and dispersion |
| 621.436.038.5 | uređaji za ubrizgavanje goriva u dizelov motor | diesel engine fuel injection devices |
| .001.572 | gledište ispitivanja na teorijskom modelu | theoretical model investigation viewpoint |
| .001.575 | gledište ispitivanja na materijalnom modelu | real model investigation viewpoint |
| 532.525 | istjecanje iz sapnica | fluid flow through nozzles |
| 516.3 | mrežni sistem prostornih koordinata | mesh system of space coordinates |

**Authors**
prof. dr. sc. Ivan Filipović,
doc. dr. sc. Boran Pikula,
doc. dr. sc. Dževad Bibić
Faculty of Mechanical Engineering Sarajevo,
Department for IC Engines and Vehicles,
Vilsonovo šetalište 9, 71 000 Sarajevo, Bosnia and Herzegovina
tel./fax. +387 33 650 841;
e-mail: fillipovic@mef.unsa.ba, bibic@mef.unsa.ba

**Received**
15/09/2010

**Accepted**
06/05/2011