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ENERGY LOSSES IN FUEL INJECTOR

Abstract

New demands regarding reducing emissions of pollutants from motor vehicles in road transport lead to requests for continual improvement of technical solutions of the IC engine on one hand, as well as using of alternative fuels on the other. Application of alternative fuels in IC diesel engines could be different and it makes a conclusion based on necessity of well knowing fuel characteristics and its influences on injection characteristics. Based on analysis of different used alternative fuels, it has been noticed that basic parameters of fuel injection process, like injection pressure, injection duration, fuel injected amount, etc. were changed, influencing combustion process in the IC diesel engine. According to these facts, in order to make an optimal combustion process in the IC diesel engine, it is necessary to set up fuel injection system.

A special part of fuel injection system is the injector, where transformation from potential to kinematic energy of fuel is conducted, with significant energy losses. Therefore special attention was dedicated to processing experimental results, first of all to shape the injection rate, as well as other mentioned injection characteristics. After analysis, a definition of energy losses in the injector was done and presented in the paper.

1. Introduction

One among the 20th c. features is an absolute domination of oil i.e. of its products, as the source of drive energy for vehicles and machinery. Oil has deserved a prime position among energents owing to its high heating power, considerable distribution of reservoirs, and a relatively easy exploitation and handling. Oil is also apt for various kinds of processing, providing a wide range of fuels for different purposes, which is particularly significant for application in internal combustion engines, especially demanding when it comes to the drive fuel quality.

Apart from limited reserves of fossil fuels, another important property of today's energy-related situation i.e. production and use of energy from fossil fuels, is associated with environmental issues. Namely, combustion of fossil fuels generates considerable environmental pollution, and, when it comes to traffic and transportation i.e. types of vehicles driven by internal combustion engines, it may be established that considerable technological advancements have to a large extent resolved the problems of the emission of pollutants, such as hydrocarbons, heavy metals, soot particles, etc. Still, unresolved is the issue of carbon dioxide emission, polluting environment by contributing to the greenhouse effect. Thus really cannot be resolved entirely with the application of fossil fuels, because their thermal energy comes from carbon combustion. Carbon dioxide emission is, therefore, an inevitable result of all fossil fuels combustion processes.

Reducing the emission of main pollutants in motor vehicles' exhaust gases was achieved by using modern engine technological systems, primarily the fuel injection system, but also the system of subsequent exhaust gases treatment. In such a way, as regards motor vehicles, in the past decade we may find various systems enabling the meeting of European standards in terms of exhaust gases emission, known as Euro 1, Euro 2, Euro 3 and Euro 4.

The other direction in the reduction of pollutants from motor vehicle exhaust gases leads through the application of alternative, preferably renewable, energy sources. There is an intensive search today for new, renewable energy sources, and also alternative fuels, to be used primarily in motor vehicles instead of oil and its products. For the time being, the most topical alternative fuels are: propane-butane, popularly known as auto-gas; methanol, ethanol, bio-gas and bio-diesel, methane, i.e. natural gas. Hydrogen is considered to be the solution for a more remote future, being by far the best fuel in many ways. Both of these roads require extensive and costly research, as well as major investments into production technologies and exploitation infrastructure.

Apart from a number of requirements for the application of a given alternative fuel, it must be as similar as possible to the conventional fuel in question. This reduces investments into engine modification necessary for switching to the alternative fuel. In keeping with this requirement, the so far research has shown that holding the most prospects among alternative fuels are the so called bio-fuels i.e. fuels obtained from biomass. These fuels may be used in engines, while their heating power is very similar to that of the given conventional fuels. Widely used today are two kinds of bio-fuels: alcohols and bio-diesel. The most important thing to point out for these fuels is that both alcohols and bio-diesel may be used individually, or as an addition to conventional fuels. Owing to their favourable environmental properties, while using bio-diesel, it is possible to achieve reduced emission of nearly all pollutants in exhaust gases, apart from NOx ,recording a relative increase with regard to emissions when applying conventional fuel (up to 10 %).

2. Properties of Alternative Fuels

Bearing in mind the so far realizations, briefly summarized in the previous chapter, one may conclude that the optimal choice today is the use of alternative fuels not requiring any engine modification. However, alternative fuels have different properties which may to a large extent contribute to the change of engine parameters, such as engine power, specific fuel consumption, etc. By knowing all the relevant fuel properties, it is possible to make an analysis of the impact of characteristic values determining impact of fuel composition on engine performance, while a segment of the said analysis is by all means also the definition of energy losses through the injector.

For performing the said analysis, used were three fuel types: conventional diesel fuel, marked as Fuel 1; alternativne fuel, marked as Fuel 3, and a blend of conventional diesel fuel and alternative fuel to the ratio of 50:50, marked as Fuel 2. The basic fuel properties obtained as a result of the measurement in case of using the said fuels are shown in Table 1.

Table 1: Characteristic properties of fuels used for the analysis

Property	Fuel 1	Fuel 2	Fuel 3
Density, *kg/m*^{3} at temperature of 30 °C	817,26	842,76	868,25
Kinematic viscosity *mm*^{2}*/s* at temperature of 30 °C	3,2278	4,1645	5,5069
Dynamic viscosity *mPas* at temperature of 30 °C	2,638	3,5087	4,7414

For the fuels whose properties are indicated in Table 1, an impact analysis was performed of the characteristic indicators of the injection system and the engine, to be presented in the following chapter.

3. An Analysis of Parameters of the Injection System and the Internal Combustion Engine

3.1 Basic Indicators

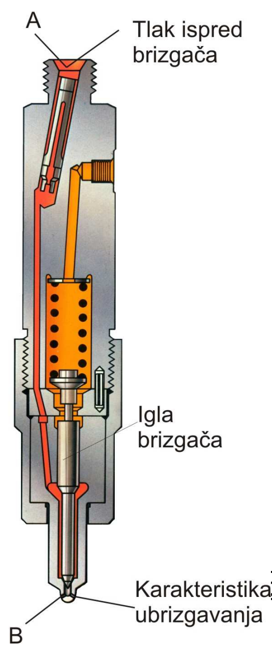
In the previous chapter, we have shown the values of densitiy and viscosity for three different fuels. These fuel properties have a considerable impact on the injection process, especially in the use of a standard diesel fuel supply system. It is known that the beginning and duration of injection, the volume of injected fuel and the quality of fuel dispersion in the combustion chamber are directly dependent on the above fuel properties. Lower heating value of alternative fuels with regard to fossil diesel fuel causes loss of the engine power which may be compensated for by a larger volume of the injected fuel. The compensation should be done in such a way as to avoid the negative impact of prolonged injection time on the combustion start.

Furtherly, testing of the parameters of the injection system has shown that a cyclic fuel supply, medium value of injection properties, injection duration expressed through the camshaft rotation angle and pressure at the end of the high pressure pipe increase with an increased share of the alternative fuel in the fuel blend i.e. towards a complete exclusion of the conventional diesel fuel. Apart from the expected reduction in the emission of exhaust gas pollutants, but also higher emission of NOx, optimizing the pre-injection angle, compensated for are all the drawbecks of using alternative fuel on a non-adjusted fuel injection system.

3.2 Defining Energy Losses in the Injector

A special segment of the research was the analysis of energy losses in the injector. Injector design (its structural appearance) is shown in Figure 1. Namely, from the viewpoint of injection process optimization, most important is the injection system, whose task it is to ensure a good quality dispersion of the fuel jet. It is therefore necessary to ensure a high potential energy of the fuel (achieved through high pressure before the injector – position A on Figure 1), capable of transforming, with as little losses as possible, into high kinetic energy of the fuel jet (achieved through high speed of the fuel jet – position B in Figure 1), injected into the engine’s operating space. The said transformation of potential fuel energy into kinetic energy of the jet most frequently defined through loss coefficient through the injector, was the purpose of our research.

Figure 1: Injector cross section with locations for measuring characteristic parameters
/Pressure before injector, Injector needle, Injection property/



In order to resolve the problem properly, it was necessary to conduct measurements during which the following pieces of information were gathered:

- injector needle path,
- pressure at the end of high pressure pipe,
- injected fuel volume,
- signal injection characteristics,
- injection start and duration,
- fuel temperature in low pressure reservoir of the high pressure pump,
- rotation velocity of the injection system high pressure pipe.

As an example of experimental results in the case of full load and high pressure pump rotation velocity of 900 o/min, Figure 2 indicates characteristic parameters of the injection system, as follows: injector input pressure and processed signal of injection characteristics. By analyzing pressure curve at injector input, one may conclude that in case of using Fuel 3, due to higher density; dynamic and kinematic viscosity, there occurs higher maximum pressure in the fuel injection system. Also, due to the said fuel properties, one may observe a faster pressure increase before the injector in case of using Fuel 3, leading to an early injection start, but also somewhat longer injection duration. Injection duration in case of Fuel 3 is 2.68 ms, whereas in case of Fuel 1, it is 2.66 ms.

Knowing pressure in the injection system before the injector, injection characteristic, volume of injected fuel, injector needle path, defining the geometric flow section through which fuel leaves the injection system injector and is injected into the operating space, by using equation (1) for injection characteristic:

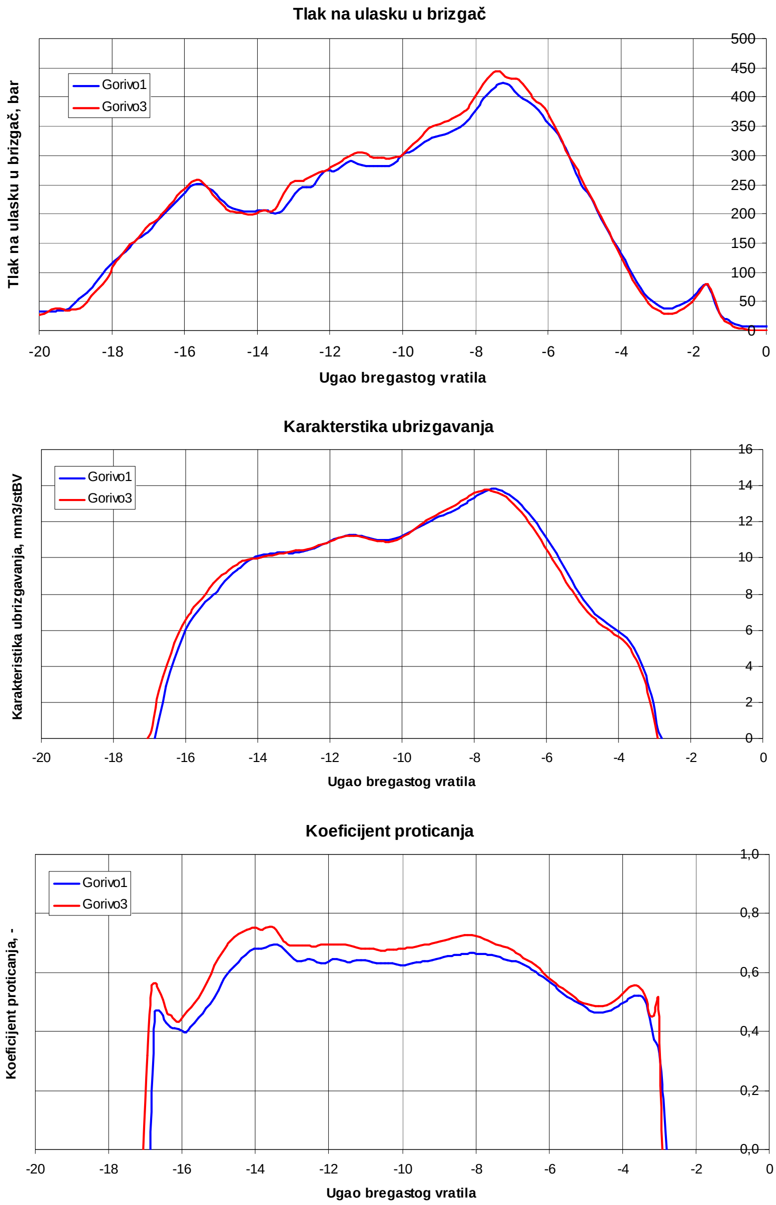
$$\dot{V}_c = \mu_b A_b \sqrt{\frac{2}{\rho}(p_{II} - p_z)}$$

where: $\mu_b A_b$ - effective injector flow section, p_{II} – fuel pressure in the injection system before the injector and p_z – pressure of the operating space into which fuel is injected (internal combustion engine or test tubes), one may calculate flow coefficient μ_b (total loss), shown in Figure 2 for a particular operating regime of the injection system.

By analyzing results referring to flow coefficient shown in Figure 2, as well as impact values shown in equation (1), the following conclusions may be drawn:

- at the beginning of injection process, characteristc impact on flow coefficient shown in Figure 1, and impact values, with an abrupt increase of the flow coefficient, reaching a certain initial maximum, and then dropping slowly, which may be explained by the impact of changeable geometric flow section at injector needle opening. Namely, by lifting injector needle from its seat, minimal flow surface is just below the very injector needle seat on conical surfaces, causing gradual increase of the flow surface, with major losses.
- further lifting of the injectior needle causes geometric flow section through which the fuel is pouring, turning into nozzle in the injector body. This flow surface is achieved already at 1/3 of the injector needle path. During most of the injection process, the said surface constitutes critical flow section. Given that we are here dealing with a constant flow surface, it is interesting to note that flow coefficient (loss) is increasing, and then dropping. The said fact is justified by change in the pressure before the injector needle.
- at the end of the injection process, in order to efficiently end the process, due to abrupt pressure decrease in the injection system just before the injector, there occurs lowering of the flow coefficient (loss increase) whose change may be described in a completely analogous manner as in lifting injector needle at the beginning of the injection process.

Figure 2: Pressure before injector, injector law and discharged coefficient at full load regime and speed of 900 rpm



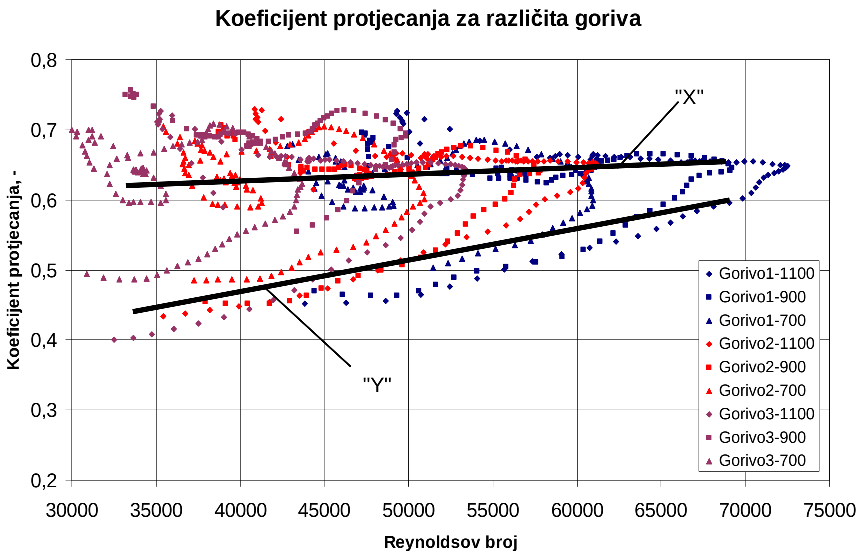
/Injector input pressure, Fuel, Camshaft angle, Injection property, Flow coefficient/

Although significant changes of fuel properties were observed, through density, kinematic and dynamic viscosity, the presentation of results in Figure 2 has enabled us to spot the change in characteristic parameters of the injection system. For a better quality analysis of the impact of flow coefficient in the function of fuel type, and hence also fuel properties in Figure 3, shown are energy losses in the injector in the function of *Re*, fuel type and rotation velocity of the high pressure pump in the fuel injection system. It is important to point out that all the results refer to the case when the injector needle is maximally lifted, while Reynolds' number is defined using equation (2).

$$Re = \frac{\rho w d}{\mu}$$

where: ρ – fuel density, μ – dynamic viscosity, *d* – nozzle diameter, *w* – fuel jet flow velocity.

Figure 3: Energy losses in the injector depending on fuel type and speed regimes



Flow coefficient for different fuels, Flow coefficient, Reynolds' number, Fuel (…)

Based on results shown in Figure 3, one may observe that the path of the flow (loss) coefficient is in the function of Reynold's number. Especially interesting is the different character in the period of increase of the fuel flow speed through the injector (curve „X“, Figure 3) with regard to that of the speed's decrease (curve „Y“, Figure 3). This may be explained by the character of the fuel flow through the injector. This enables other speed regimes also to be analyzed parallely. It may be observed in Figure 3 that reduction in the speed of the high pressure pump achieves lower maximum pressure in the injection system, just before the injector. This enables complete definition of energy losses in the injector for different fuel types, different speed regimes and load regimes.

These losses constitute total injector losses. Particularly interesting is their distribution along the injector, which may be determined by a combination of experiments and modelling the process of fuel flow in the injector.

4. Conclusion

The paper briefly presents the importance of using alternative fuels for the purpose of reducing pollutants' emission from internal combustion engines' exhaust gases, while a special attention is paid to those alternative fuels the use of which does not require modifications of the internal combustion engine injection system. Based on the adopted fuels, defined by various physical properties, measurements have been performed pointing to conclusions on their impact on indicators of the injection system and internal combustion engines.

In order to determine energy losses in the injector itself and the impact analysis of various fuels, velocity and load regimes, certain experimental measurements have been performed. After processing experimental results, the flow coefficient has been determined, while the method for its determination is presented in the paper. The character of flow (losses) coefficient in a given injector for the known operating conditions is also presented in the paper, to be used by the injector designers in order to increase flow coefficient i.e. reduce injector losses, through the form of its particular parts.

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665.3.094.942	biodizelsko gorivo, metilni esteri masnih kiseline	biodiesel fuel, fatty acids methyl ester (FAME)
665.753.4	dizelsko gorivo	diesel fuel
621.436	dizelov motor	diesel engine
621.436.038.3	atomizacija i ubrizgavanje biodizelskog goriva tlakom	biodiesel fuel atomization and fuel injection by pressure
532.525	istjecanje iz sapnica	flow through nozzles

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