NUMERICAL AND EXPERIMENTAL ANALYSES OF INJECTION CHARACTERISTICS USING JET FUEL

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Abstract. The article presents experimental and numerical analysis of the diesel and aviation fuel Jet A-1 injection characteristics. The injection experiments were conducted using a high pressure common rail injection system. The injection characteristics were analyzed using an injection rate measuring instrument according to the Bosch method. The injection rate, cycle injection quantity, injection delay and injection duration were analyzed at 85.0 MPa, 115.0 MPa and 140.0 MPa injection pressures and 1.3 ms injection energizing time. As the results show, the peak mass injection rate of jet fuel was at 85.0 MPa injection pressure lower by 2.3 % only compared to diesel fuel. By increasing the injection pressure this difference decreases. However, the volumetric injection rates were slightly lower for diesel fuel. The injection delay was 0.3 ms for diesel fuel and 0.27 ms for jet fuel at 85.0 MPa and 115.0 MPa injection pressure, and 0.3 ms for both fuels at 140.0 MPa injection pressure. The injection duration in all cases was longer than the energizing duration of the injector. The discharge coefficient of jet fuel was by 6.5 % higher than that of diesel fuel. The experimental results were compared with the numerical simulation results. The common rail injector model was created with AVL BOOST Hydsim software. The measured pressure in the injection duct was used to validate the model in addition to the discharge coefficient and injection rate. The comparison of the simulated injection rate with the experimental data shows that the Boost-Hydsim common rail injector model gives good results for both standard diesel fuel and jet fuel.

Keywords: diesel fuel, jet fuel, common rail injection system, injection rate, modelling.

Introduction

In 1988, the NATO countries decided to move towards the use of a single fuel for all land-based military aircraft, vehicles, and equipment when employed for the army actions on the battlefield. In 2004, the NATO Pipeline Committee adopted the Single Fuel Policy [1]. The aim of the original Single Fuel Concept is to simplify the supply chain for petroleum products in the NATO nations and to achieve maximum both aircraft and ground equipment interoperability by using of a single fuel, namely JP-8 (F-34) military jet kerosene produced from the civil fuel Jet A-1.

The experimental studies of the aviation jet fuel using in diesel engines on engine performance and exhaust emissions have been carried out by many researchers. The results obtained with S60 engine showed that the use of JP-8 fuel leads to lower NO_x and PM emissions and shifts the NO_x-PM trade-off favourably for almost all performance conditions [2]. The test results of a 558 kW, B-46-6, supercharged, 12-cylinders, CIDI engine showed that the torque and horsepower of diesel fuel can be matched with fuel economy penalty lower than 4.5 %, by increasing the volumetric fuel delivery to compensate the lower density of JP-8 fuel [3]. The ignition of JP-8 is slightly longer than that of diesel fuel due the lower cetane number even though one could expect that JP-8 may have shorter ignition delay due to superior vaporisation and, thus, faster mixing [4-5].

Therefore, in order to better identify the effect of the fuel properties on the diesel combustion process, prior need investigated injection process and flow characteristics. Aviation jet fuel is characterized by lower viscosity, density, surface tension than diesel. These differences can have an influence on injection and spray formation characteristics.

The experimental studies of influence of biodiesel fuel properties on the injection mass flow rate of a diesel common-rail injection system have been carried out by Boudy and Seers [6]. The results show that fuel density is the main property that affects the injection process, such as total mass injected and pressure wave in the common rail system. Blends of ethanol and diesel fuels demonstrate a lower viscosity of fuels [7]. Decrease in fuel viscosity changes the injection spray parameters, decreasing the spray penetration and increasing its initial angle. Dernotte et al. [8] present an experimental investigation of the influence of fuel density and fuel viscosity on the flow characteristics and on the spray development process generated from a high pressure diesel injector. The results show that increasing fuel viscosity leads to a decrease of the discharge coefficient for low injection pressures while density is the main parameter driving the mass flow rate. The dense and viscous fuels tend to induce a longer spray tip penetration with a more narrow spray angle.

An experimental study carried out in an optically-accessible, single-cylinder, heavy-duty diesel engine with a common-rail injection system showed that the JP-8 fuel spray tip penetration was shorter by nearly 16 % for injection pressure of 30 MPa and 10 % for higher injection pressure of 140 MPa compared to the normal diesel fuel. The lower spray tip penetration was compensated by 15.9º to 6.2º wider spray angle of JP-8 under considered fuel injection pressures than that of diesel fuel mainly due the faster vaporization characteristics of JP-8 (4). The widely differing chemical and physical properties of JP-8 contribute to higher fuel-air mixing rate and improve atomization, resulting from shorter spray tip penetration and a wider spray angle [9].

Simulation plays a central role in the analysis of complex systems like the common rail injection system. It helps significantly in answering different questions concerning the behaviour of components such as pumps and injectors.

The simulation tests performed by Boudy and Seers [10] on a four cylinder common-rail injection system model with a single and triple injection strategies further show that fuel density is the main property that affects the amount of total mass injected and pressure wave fluctuation. Researchers have determined that viscosity and bulk modulus of the fuel also have influence on the injection process, but to a lesser degree because in that experimental work the common-rail injection system enabled to have more stable injection parameters. However, which physical parameter of the fuel will play a bigger role in the injection process also depends on the design of the injection system and its performance conditions.

Therefore, due to significant differences in the fluid properties when compared to the conventional diesel fuel, the rates of injection from these alternative fuels are necessary to optimize the combustion process in the compression ignition engine. The aim of the research was to investigate the injection characteristics of diesel and jet fuels in high pressure injection system.

Materials and methods

A low sulphur diesel fuel (DF) and Jet A-1 fuel (Jet) were used in this study. The relevant physical properties of both fuels are presented in Table 1.

Table 1

Relevant fuel properties

Fuel properties at 15 ºC	Diesel fuel	Jet fuel
Density, $kg \cdot m^{-3}$	830	798
Bulk modulus, $N \cdot mm^{-2}$	1460	1275
Kinematic viscosity, $mm^2 \cdot s^{-1}$	10	1.75

The fuel injection experiments were conducted using a high pressure common rail injection system able to generate up to 160 MPa rail pressure. Fig.1 shows the injection rate test rig. The injection rates of the diesel and jet fuels were measured and analysed using an injection rate measuring system based on the Bosch method [11]. The injection rate measuring method is based on measuring a dynamic increase in pressure produced by fuel injection into a measuring tube filled with fuel. The fuels have been injected with the following pressures: 85.0 MPa, 115.0 MPa and 140.0 MPa, the injection duration was 1.3 ms. The back pressure in the tube was adjusted to 4.0 MPa in order to simulate injection pressure corresponding to the real value of the pressure in the engine combustion chamber during injection. The results of 100 injection cycles were recorded and overaged for the analysis. The injection quantity was obtained from the mean value of 1000 continuous injections, measured by a precision scale. To obtain a good estimation of the experimental errors three repetitive measurements were carried out at the same test point.

The discharge coefficient C_d was calculated by dividing the measured mass flow rate by the theoretical mass flow rate.

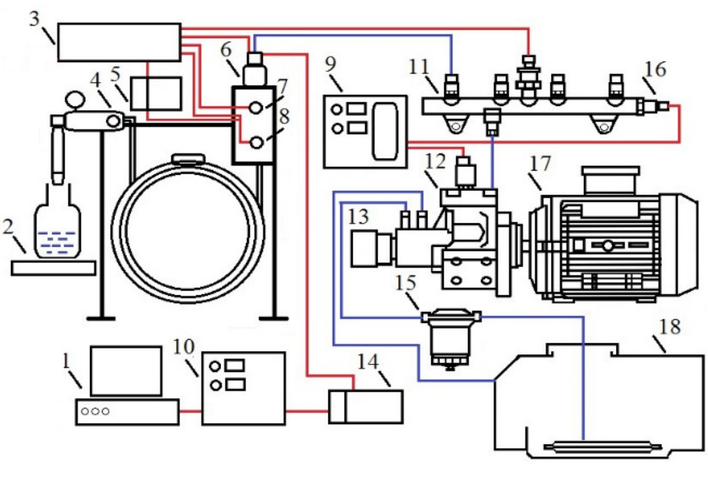

Fig. 1. **Scheme of the fuel injection rate test rig:** 1 – PC; 2 – electronic scale; 3 – data acquisition module; 4, 8 – pressure sensors; 5 – charge amplifier; 6 – injector; 7 – temperature sensor; 9 – fuel pressure control unit; 10 – injector driver; 11 – fuel rail; 12 – HP pump; 13 – pressure regulator; 14 – NI 9161 chassis; 15 – fuel filter; 16 – rail pressure sensor; 17 – EC motor; 18 – fuel tank

The simulations of the injection process were performed with AVL BOOST Hydsim software which enables to model integrated systems involving mechanical, electrical, thermal, hydraulic and other components. The simulation software uses libraries to define each component of a system. This definition is used to predict the behaviour of the component and requires knowing its characteristics: physical, mechanical, electrical, etc. Boost-Hydsim model of the common rail injector is show in Figure 2. In order to reproduce an accurate behaviour with the injector model, each one of its internal elements needs to be geometrically and hydraulically characterized.

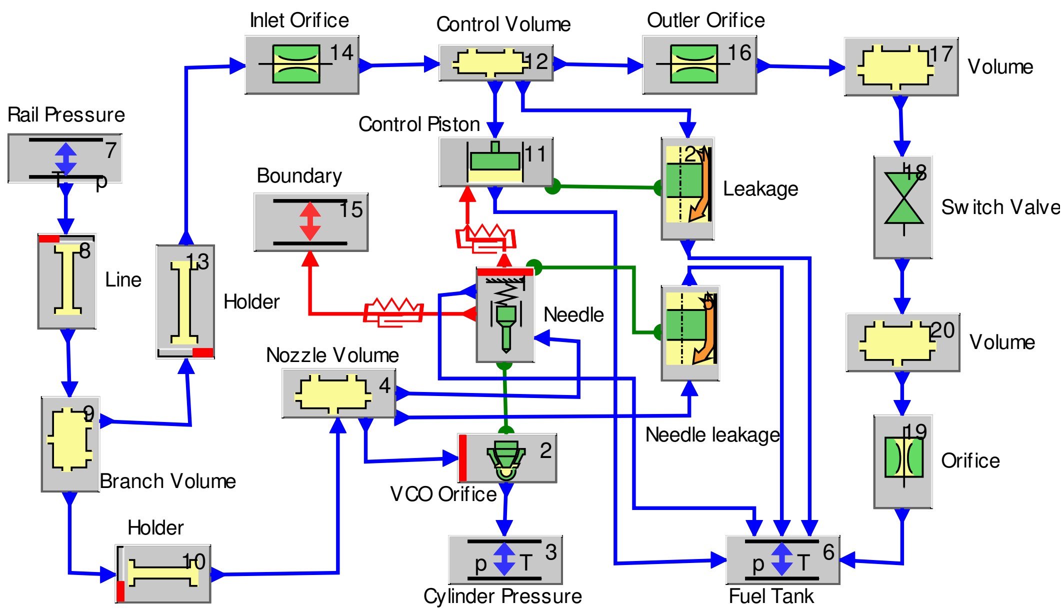

Fig. 2. **Boost-Hydsim model of the common rail injector:** injector type CRIN2-16, nozzle type DLLA 140P1790

Results and discussion

Fuel injection and atomization processes in Diesel engines have a major impact on fuel consumption, exhaust emissions and noise production.

Fig. 3 shows the injection rate profile of all fuel tested at various injection pressures. When the injection pressure increased, the maximum injection rate increased for both fuels tested. But at the same injection conditions, the peaks of the mass injection rate of jet fuel were slightly lower compared to diesel fuel. At 85.0 MPa injection pressure the maximum mass injection rate of jet fuel was lower compared to diesel fuel by 2.3 % only. By increasing the injection pressure this difference decreases. At 145.0 MPa injection pressure the maximum mass injection rate was practically the same for both diesel and jet fuels. However, the volumetric injection rates were slightly lower for diesel fuel. It is caused by higher density of the diesel fuel.

When the energizing process finishes the needle descends to its seat, and the viscous forces of the fuel oppose the closing of the injector. As seen in Fig. 3, since the viscosity of jet fuel is lower than diesel fuel, less time is needed to close the injector due to the viscous force less slowing down the needle movement.

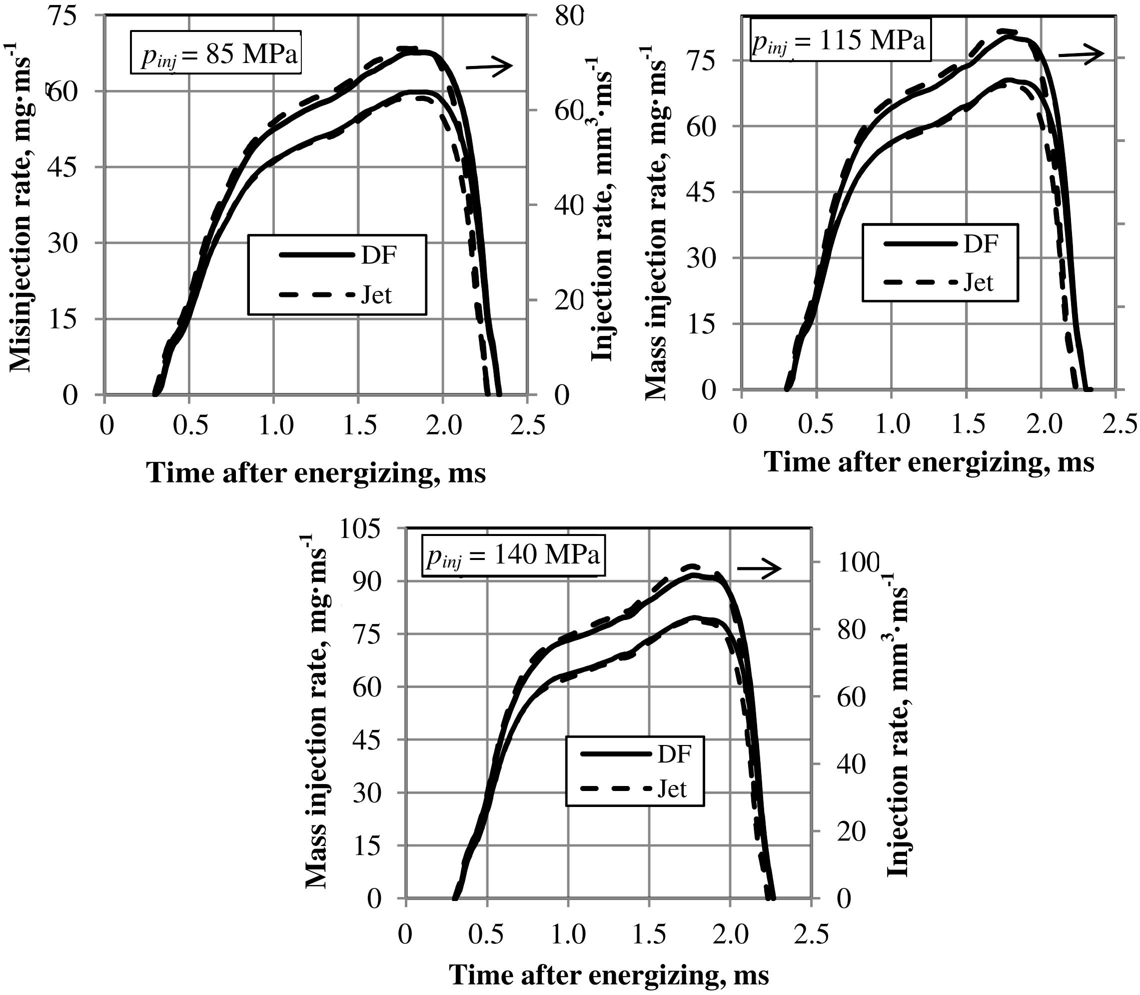

Fig. 3. **Effect of the injection pressure and fuel type on the injection rate: back pressure 4.0 MPa, energizing time 1.3 ms**

At injection pressure 85.0 MPa and 115.0 MPa the injection delay for diesel fuel was 0.3 ms and for jet fuel 0.27 ms. When the injection pressure increased to 140.0 MPa, the injection delay for both fuels was 0.30 ms. The injection delay is the time interval between the start of energizing and the start of injection that was obtained from the injection rate characteristics. In contrast to the mechanically controlled injection systems, the common rail injector needle rise does not depend on the pump induced pressure rise, but on the pressures acting on the control plunger and nozzle needle difference after the solenoid energizing. The lower density and viscosity of jet fuel are able to increase the fuel flow processes and caused slightly shorter injection delay than diesel fuel. The cyclic injected masses were for diesel fuel 85.5 mg, 100.3 mg and 112.7 mg at 85.0 MPa, 115.0 MPa and 140 MPa injection pressure correspondently. The jet fuel injection quantities were lower than diesel fuel by 4.3 %, 4.9 % and 3.2 % at 85.0 MPa, 115.0 MPa and 140 MPa injection pressure correspondently. However, the injected volumes for jet fuel were lower only at 85.0 MPa and 115.0 MPa injection pressures. At 140.0 MPa injection pressure volumetric injection quantity was the same for both fuels.

The injection duration for both test fuel does not differ significantly. Real fuel injection duration was obtained by analysing the injection rate characteristics, and it is the time interval between the start and the end of injection. The injection duration was longer by 1.6 % for diesel fuel. The real injection duration in all cases was longer by 59 % than the energizing duration of the injector (t_{energ} = 1.3 ms) due to the response time of the injector solenoid for the control signal.

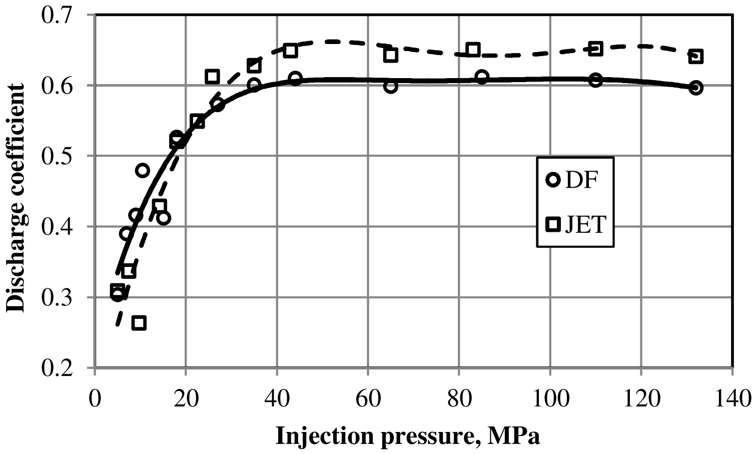

Fig. 4. **Discharge coefficient versus injection pressure for diesel and jet fuels**

Fig. 4 shows the effect of the injection pressure on the discharge coefficient C_d. It can be seen that the discharge coefficient was at full rise of the needle for jet fuel by about 6.5 % higher than that for diesel fuel. Discharge coefficient increases are probably related to the lower density and viscosity of the jet fuel. These experimentally determined discharge coefficients were used to simulate the injection characteristics.

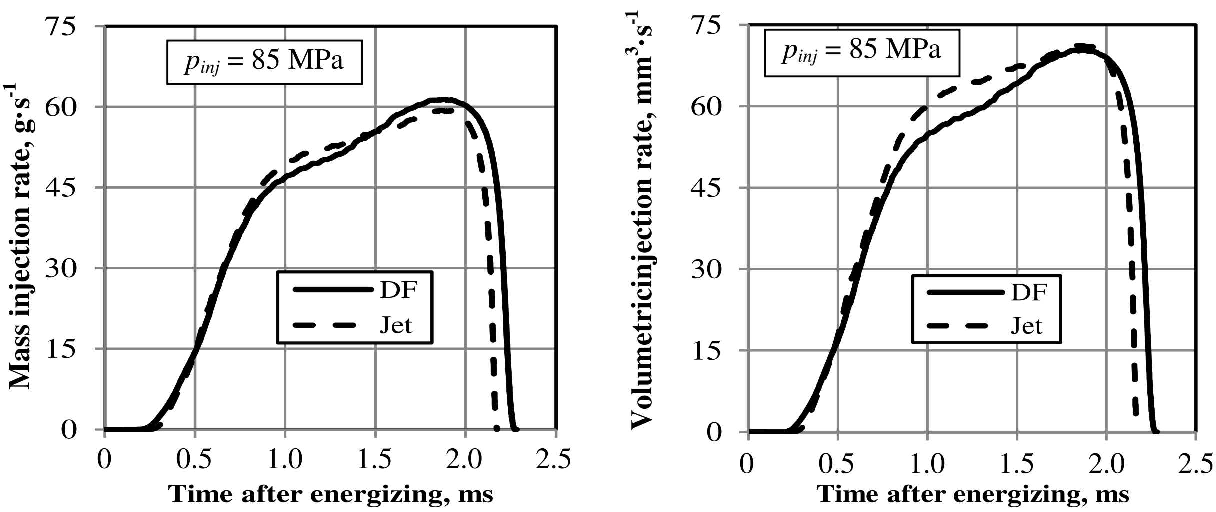

Fig.5. **Simulated diesel and jet fuel mass and volumetric injection rate**

Fig. 5 shows simulated injection rate for diesel and jet fuels at 85.0 MPa injection pressure. It can be seen that the higher density of diesel fuel causes the mass injection rate to be higher. Similar results were obtained experimentally (Fig. 3).

The measured pressure in the injection duct was used to validate the model in addition to the discharge coefficient and injection rate determined using the Bosch method. As shown in Figure 6, the end of injection is characterized by fast pressure increase (“water hammer effect”) caused by the rapid closing of the injector.

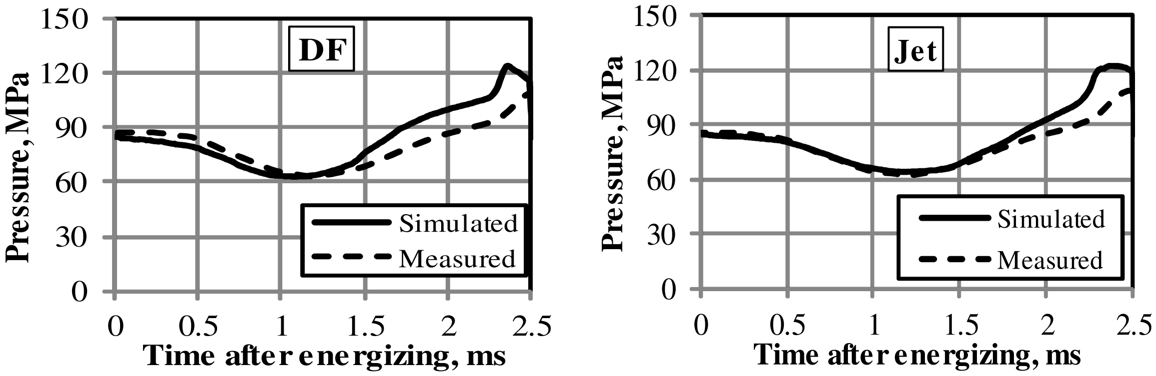

Fig.6. **Measured and simulated pressure in injection duct**

Since the injection system must inject the proper amount of fuel, it is important that the results provided by the model match the experimental data with a good accuracy. The simulated injection quantities were for diesel fuel 85.8 mg and for jet fuel 81.7 mg. Therefore, it can be concluded that simulation and measurement correspond well.

Conclusions

1. The peak mass injection rate of jet fuel was at 85.0 MPa injection pressure lower by 2.3 % only compared to diesel fuel. By increasing the injection pressure this difference decreases. However, the volumetric injection rates were slightly lower for diesel fuel.
2. The injection delay was 0.3 ms for diesel fuel and 0.27 ms for jet fuel at 85.0 MPa and 115.0 MPa injection pressure, and 0.3 ms for both fuels at 140.0 MPa injection pressure. The injection duration in all cases was longer than the energizing duration of the injector.
3. The discharge coefficient of jet fuel was by 6.5 % higher than that of diesel fuel.
4. The comparison of the simulated injection rate with the experimental data shows that the Boost-Hydsim common rail injector model gives good results for both standard diesel fuel and jet fuel.

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