

Article

Impact of Synthetic Paraffinic Kerosene Blends on the Injection Rate in Common-Rail Systems of Reciprocating Engines

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Abstract

This study analyzes the injection behavior of fossil and sustainable aviation fuel blends, in comparison with conventional diesel fuel, using a common-rail injection system applied to reciprocating engines. Neat commercial diesel and Jet A1 were tested as fossil fuels. A neat Fischer–Tropsch Synthetic Paraffinic Kerosene was tested and blended with Jet A1. Another alternative fuel, Hydrotreated Vegetable Oil, was also blended with Jet A1. The blending proportion was established to meet 51 as the derived cetane number, as required for fuels used in diesel reciprocating engines. Experimental tests were carried out under an energizing time of 2 ms at injection pressures between 50 and 110 MPa, with a fuel temperature ranging from 293 to 313 K, and a constant back pressure of 5 MPa, using a 130 μm single-hole injector. The results show that kerosene fuel exhibits slightly lower injection rates and total injected mass than diesel fuel, mainly due to their lower density. Under low-pressure conditions, an increase in hydraulic injection delay with diesel fuel is observed, mainly at the highest tested temperature. Mass flow rate, hydraulic injection delay, injection duration, total mass injected, and nozzle discharge coefficient do not show significant variations within the tested temperatures. Fossil kerosene fuel and its blend with Synthetic Paraffinic Kerosene show slightly higher injection rates. Overall, the results indicate that both neat kerosene and the studied blends may achieve injection characteristics comparable to diesel fuel, supporting their technical feasibility in reciprocating engines within the framework of the Single Fuel Concept.

Keywords: fuels; kerosene; diesel; injection rate; reciprocating engines



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1. Introduction

The use of renewable kerosene fuel, commonly denoted as sustainable aviation fuels (SAFs), in compression ignition engines, which are traditionally not designed for this type of fuel, constitutes a novel and still scarcely explored field. This application for kerosene fuels shows great potential, opening new opportunities in sectors such as light air transport, unmanned aerial vehicles (UAV) for surveillance, and ground support equipment (GSE) for aviation. In this context, different studies have analyzed some ignition characteristics [1,2] and pollutant emissions, both gaseous and particulate matter [3], when employing SAF in these types of propulsive systems.

Performance assessment of these fuels requires a comprehensive approach that includes bench testing [4,5], physicochemical characterization [6], simulations [7], real-condition trials [8], compatibility studies with different materials [9,10], and finally their certification [11,12]. For example, tests carried out on an engine bench make it possible to measure key parameters such as mass flow rate of high-pressure injection systems or engine performance, or even parameters of the combustion process, such as ignition delay, heat release rate, and pollutant emissions under testing-controlled conditions [13].

In this work, particular attention is given to the fuel injection rate, which was experimentally obtained, and to the estimated nozzle discharge coefficient (C_d) of the injector, by employing different neat fuels and blends under different working conditions. Both parameters are influenced, among other factors, by nozzle geometry [14], injection pressure [15] and fuel temperature [16], back pressure in the volume where the fuel is injected [17], and the physicochemical properties of the fuel used [18,19].

The knowledge and study of the fuel injection process provide information about how the fuel is introduced into the combustion chamber [20]. Fuqiang Bai et al. (2017) [21] investigated the effects of injection rate profile on combustion process and emissions in a diesel engine, whereas Taixue Bei et al. (2022) [22] focused on the effects of injection timing and fuel injected on the combustion process and emissions produced in a two-stroke direct injection engine using kerosene as fuel.

Furthermore, the fuel injection rate represents the starting point for the study of fuel spray formation dynamics. In this context, Liu et al. (2023) [23] demonstrated through an Artificial Neural Network-based model that predicting the injected mass is essential to characterize spray performance parameters (such as cone angle, liquid length, and Sauter mean diameter), thereby confirming the direct dependence of spray behavior on the injection rate. Similarly, Naruemon et al. (2020) [24] analyzed the effects of different injection rate shapes on the diesel spray mixing process through numerical simulations, highlighting how variations in the injection profile strongly influence spray development and fuel–air mixing efficiency. Comparing injection rates obtained with different fuels allows us to identify key differences in their behavior, providing crucial information on the technical feasibility of replacing diesel fuel with sustainable kerosene fuels in existing injection systems. Yu et al. (2016) [25] compared the macroscopic spray characteristics of kerosene and diesel fuels, observing significant differences in spray penetration, velocity, and angle, which highlights the importance of considering the injection rate when assessing the technical feasibility of replacing diesel with sustainable kerosene in existing injection systems.

The accurate determination of the fuel injection rate enables the calculation of several fundamental properties of the injection process, from both hydrodynamic and thermodynamic perspectives. These parameters are essential for understanding processes such as spray atomization, air–fuel mixing, and subsequent combustion. Some of them are directly related to the injector’s hydraulic characterization, such as spray momentum flux, discharge coefficient, spray exit velocity, and Reynolds number [26]. Others, instead, mainly describe properties of the fuel or the injection system, for example, the fuel bulk modulus [27].

The determination of both the fuel injection rate and the estimation of the nozzle discharge coefficient with modern fuel injectors lays the groundwork for future research aimed at the replacement of conventional fossil kerosene with SAF in injection systems of reciprocating engines. Although these engines have been originally designed for using diesel fuel, their proximity to the well-known approach Single Fuel Concept (SFC), which is traditionally promoted in the defense sector for logistical and security reasons and now reinforced by new environmental policies, promotes interest in evaluating sustainable kerosene fuels in compression ignition engines.

This work is particularly relevant due to the scarcity of studies testing SAFs in diesel engines and the interest and imperative use of these sustainable fuels. The mandatory incorporation of these sustainable fuels to achieve the desired decarbonization in the transportation sector and the possibility of incorporating kerosene in diesel engines (SFC) are the main justifications for this study, considering that the characterization of the injection process is a preliminary step to evaluating the performance and emissions of these fuels. In this way, this study provides a solid starting point to deepen the understanding of these fuels under actual operating conditions, while paving the way for specific applications in light aviation, UAV, and GSE.

The work has been organized in the following way: Section 2 discusses the experimental work, which includes a description of the equipment, the methodology for determining the fuel injection rate and discharge coefficient, properties of the tested fuels, and the text matrix used in the study. Section 3 is related to the results and discussion. Finally, this work presents a summary of the main findings and conclusions.

2. Experimental Work

2.1. Experimental Equipment

A schematic of the facility and a sketch of the experimental equipment used to determine the fuel injection rate under control and reproducible operating conditions during testing are presented in Figure 1.

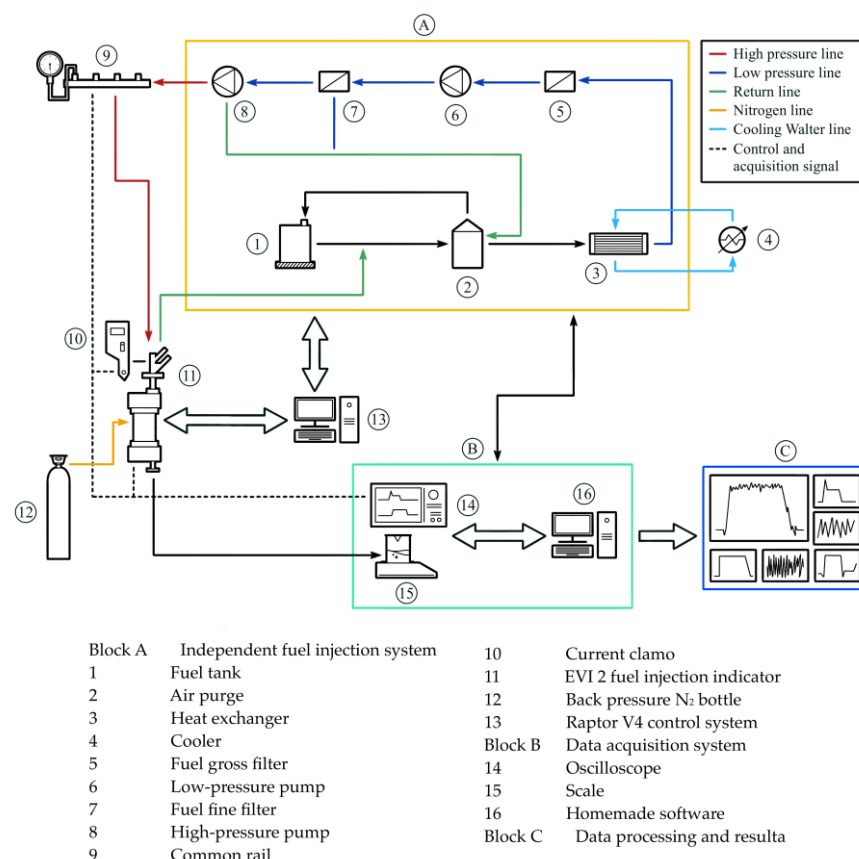


Figure 1. Experimental installation.

An independent fuel injection system (A) is responsible for the fuel supply for common-rail injection (9), while the EVI 2 fuel injection rate indicator (11) allows determination of the injection rate under back pressure conditions, which simulate those of a combustion chamber. At the same time, the injected fuel is collected and weighed on a high-precision

scale (15), enabling validation of calculated values from those parameters recorded by the EVI 2 fuel injection rate indicator (11). A pressured nitrogen bottle (12) is used to produce an inert atmosphere for regulating the back pressure within the EVI 2 fuel injection rate indicator (11).

Back pressure is necessary for reproducing the most realistic injector operating conditions. To maintain the fuel temperature at the inlet side of the high-pressure fuel pump (8), a cooling unit is incorporated (4), avoiding fuel temperature variations that could affect the results.

Finally, regulation of the complete injection system (Block A) is carried out through the Raptor V4 control system (13), which manages the injection parameters, while the data acquisition system (Block B), integrated by an oscilloscope (14), the above-mentioned precision scale (15), and a computer (16) for online data recording.

The data generated by the different parts of the system were used for calculation of the fuel rate of injection (Block C) with an in-house software (16) developed by the Clean Mobility and Thermofluids Institute (CMT) of Polytechnical University of Valencia (UPV), Spain.

The study employed specific sensors to measure the injection parameters. Back pressure (P_{back}) was recorded using a piezoelectric sensor, while rail pressure (P_{rail}) was measured with our own commercial automotive piezoresistive common-rail sensor. The injector energizing current (ET) was monitored using a current clamp, fuel temperature was measured with a Type-K thermocouple, and the injected mass, used to correlate with the mass estimated from the EVI, was measured with a high-precision gravimetric balance. The parameters measured and accuracy of the equipment described in Figure 1 are indicated in Table 1.

Table 1. Main parameters measured and accuracy of the equipment presented in Figure 1.

Parameters/Equipment	Units	Operating Range	Accuracy
Common-rail injection pressure (P_{rail})/(9)	MPa	20–200	±1%
EVI 2 Back pressure (P_{back})/(11)	MPa	1–18	±0.1
Injector energizing current/(10)	A	0.01–20	±1.5%
Temperature/(11)	K	343	±0.05
Weighted fuel mass/(15)	g	0–3000	±0.03

The method employed for measuring the injection rate using an EVI 2 fuel injection rate meter indicator (3) was proposed by Bosch, based on the use of an anechoic tube [28]. In this procedure, the injector discharges the fuel into a duct filled with the same fluid, where a piezoelectric transducer records the pressure fluctuations generated during the injection process. From these pressure signals, the instantaneous mass flow rate is determined, allowing the reconstruction of the time injection profile. Fuel mass flow rate can be expressed by Equation [29]:

$$\frac{dm}{dt} = \frac{A}{c} \times dp \quad (1)$$

where

$\frac{dm}{dt}$ —mass variation over time (kg/s);

A —Cross-sectional area of the measuring tube (m²);

dp —Pressure drop along the volume of the hydraulic unit (Pa);

c —Speed of sound in the fuel contained in the volume of the hydraulic unit (m/s).

Figure 2 shows an internal view of the EVI 2 fuel injection rate indicator (11), identifying the key sections that comprise its design.

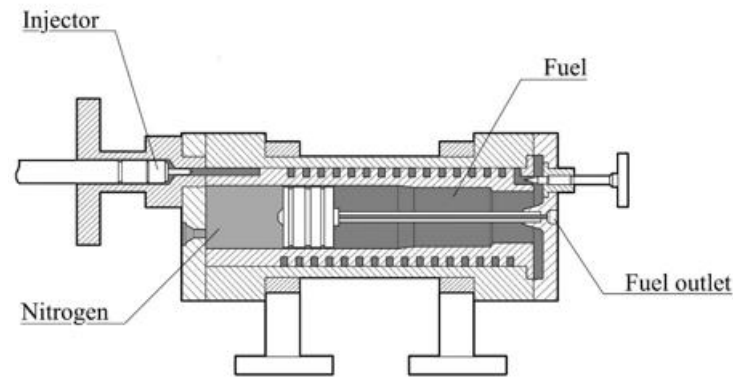


Figure 2. Scheme of the internal view of the EVI 2 fuel injection rate indicator.

2.2. Fuel Injection Rate and Discharge Coefficient Determination

The theoretical fuel injection rate $\dot{m}_{f_{th}}$ represents the fuel mass delivered per unit time and could be calculated as follows [30]:

$$\dot{m}_{f_{th}} = \int_{A_0}^{A_f} \rho_f dA = \rho_f \times v \times A_{geom}. \quad (2)$$

where

ρ_f —mean fuel density (kg/m³);

v —velocity of the fuel (m/s);

A_{geom} —nozzle geometric section area (m²);

A_0 —nozzle initial area (m²);

A_f —nozzle final area (m²).

Assuming a pressure drop across the nozzle and nearly constant density, the velocity of the fuel can be expressed using Bernoulli's principle [31]:

$$v = \sqrt{\frac{2 \times \Delta P}{\rho_f}} \quad (3)$$

$$\Delta P = P_{upstream} - P_{downstream} = P_{rail} - P_{back} \quad (4)$$

where

ΔP —pressure drop across the nozzle (Pa);

$P_{upstream}$ —upstream fuel pressure; in this case, the common-rail pressure (P_{rail}) (Pa);

$P_{downstream}$ —downstream back pressure; in this case, the back pressure within EVI 2 (P_{back}) (Pa).

Substituting Equation (3) into Equation (2), the theoretical, pressure-dependent injection rate is obtained (Equation (5)):

$$\dot{m}_{f_{th}} = A_{geom} \times \sqrt{2 \times \rho_f \times \Delta P} \quad (5)$$

To account for real losses such as friction, contraction, and cavitation, a discharge coefficient (C_d) is introduced [20]:

$$\dot{m}_f = C_d \times A_{geom} \times \sqrt{2 \times \rho_f \times \Delta P} \quad (6)$$

where

$\dot{m}_f$ —actual fuel mass flow rate (kg/s).

Discharge coefficient C_d is defined as follows:

$$C_d = \frac{\dot{m}_f}{\dot{m}_{f_{th}}} \quad (7)$$

The discharge coefficient is a dimensionless parameter that quantifies the hydraulic efficiency of the injector by comparing the actual flow (Equation (6)) to the theoretical flow (Equation (5)) predicted by Bernoulli's equation [31].

By applying the discharge coefficient to the geometric sectional area, the effective area (A_{eff}) is estimated, accounting for all these limitations. Consequently, the actual fuel mass flow rate can be expressed as follows:

$$\dot{m}_f = A_{eff} \times \sqrt{2 \times \rho_f \times \Delta P} \quad (8)$$

However, in this study, the actual fuel mass flow rate was obtained using the test facility and acquisition software, whereas the theoretical fuel mass flow rate was calculated through Equation (5) for the determination of the discharge coefficient.

Finally, the discharge coefficient can be determined using Equation (9) [32]:

$$C_d = \frac{\dot{m}_f}{A_{geom} \times \sqrt{2 \times \rho_f \times (P_{rail} - P_{back})}} \quad (9)$$

2.3. Fuels

In this study, different neat fuels and blends were tested. Regarding neat fuels, the reference fuel for compression ignition engines, i.e., diesel fuel, and for air-breathing jet engines, i.e., Jet A-1, were selected. Additionally, as was mentioned previously, the progressive incorporation of SAFs and the goal of progressing towards the concept of a single fuel has justified the use of this alternative kerosene fuel in this study. The main characteristics of the neat fuels are detailed below:

- Diesel fossil fuel (EN590) with a derived cetane number (DCN) = 51, used as a reference fuel in diesel reciprocating engines [33].
- Jet A1 fossil kerosene (DEF STAN 91-091, ASTM D1655) with DCN = 43.95, considered as a reference kerosene for civil aviation transport [34,35].
- Fischer-Tropsch Synthetic Paraffinic Kerosene (SPK-FT). Sustainable kerosene fuel (ASTM D7566) with DCN = 67.55, used as a sustainable aviation fuel for turbojet engines [36].
- Hydrotreated Vegetable Oil (HVO). Renewable paraffinic diesel (EN 15940) with DCN = 71.52, used as a sustainable alternative to conventional fossil fuel in compression-ignition engines [37]. In this study, this fuel was used exclusively for blending with Jet A1 fuel.

The aim of this study lies in the use of fuel blends with SAF, ensuring that these develop a correct combustion process. In this sense, two properties were considered as priorities to achieve this goal: derived cetane number and lubricity. For this reason, the percentage of sustainable fuels (HVO and SPK-FT) with Jet A1 were calculated in order to set a derived cetane number of 51 (minimum required for a fuel to be used in a diesel engine [33]), considering that the DCN of blends may be calculated from the volumetric contribution of each neat fuel in a blend [38]. The DCNs of the two blends tested were corroborated later with the Cetane Ignition Delay 510 instrument. Also, 2% (v/v) of biodiesel was incorporated into neat kerosene fuel and its blends to provide the lubricity required in standard EN 590. This content has been determined in previous studies [39,40]. Considering this requirement, the following fuel blends were tested:

- Jet A1 (71% *v/v*) + HVO (27% *v/v*) + 2% (*v/v*) of biodiesel.
- Jet A1 (68% *v/v*) + SPK-FT (30% *v/v*) fuel blend + 2% (*v/v*) of biodiesel.

Blending of HVO with Jet A1 fuel is justified by its growing potential as an alternative to diesel fuel in reciprocating engines used as ground service equipment in civil or military airports, owing to its enhanced properties and its ability to increase the cetane number, a key parameter for ensuring optimal combustion conditions [41,42].

The physicochemical properties of the studied fuels are presented below (Table 2). The values of density, kinematic viscosity, higher heating value, derived cetane number, and lubricity were measured experimentally.

Table 2. Main properties of neat fuels and blends.

Properties	Diesel	Jet A1	SPK-FT	HVO	Jet A1 + SPK-FT (DCN = 51)	Jet A1 + HVO (DCN = 51)
C (% w/w)	85.40	85.40	84.59	85.49	85.16	85.43
H (% w/w)	13.79	14.36	15.16	14.27	14.59	14.33
O (% w/w)	0.81	0.24	0.25	0.25	0.25	0.24
Density at 15 °C (kg/m ³)	838	794	762	780	785	791
Viscosity at 40 °C (cSt)	2.67	1.09	1.50	2.95	1.20	1.37
Higher Heating Value at constant volume (MJ/kg)	45.63	46.15	47.56	47.21	46.54	46.44
Lower Heating Value at constant pressure (MJ/kg)	42.66	43.08	44.32	44.16	43.42	43.38
Derived Cetane Number	>51	43.95	67.55	71.52	51	51
Wear Scar Diameter (μm)	488.7	507.1	511.3	503.8	483.6	505.6
Cloud Filter Plugging Point * or Freezing point ** (°C)	−17 *	−63 **	−48.8 **	−21 *	-	-

The values of density were obtained using calibrated buoys in accordance with the ASTM D4052 standard [43], while kinematic viscosity was determined with a Cannon-Fenske Routine viscometer following ASTM D445 [44]. The higher heating value at constant volume was obtained using a Parr 6050 bomb calorimeter according to ASTM D240 [45]. The lubricity was assessed using a Ball-on-Cylinder Lubricity Evaluator (BOCLE), from PCS Instruments, following ASTM D5001 [46]. The Cetane Ignition Delay 510 instrument [47] was used to determine the DCN of neat fuels and blends, following ASTM D7668 [48]. Information related to freezing point and elemental composition was provided by the REPSOL technology lab.

Regarding heating values, the calorimeter bomb provides a higher heating value at constant volume (*HHV_v*). To estimate the lower heating value at constant pressure (*LHV_p*), Equations (8) and (9) were used, where Y_h and Y_o are the mass fractions of hydrogen and oxygen in fuel, respectively, and Du_{H_2O} is the internal energy of water (2305.1 kJ/kg).

$$LHV_v = HHV_v - 9 \times \Delta u_{vap\ H_2O} \times Y_h \quad (10)$$

$$LHV_p = LHV_v - 619.42 \times Y_h - 77.43 \times Y_o \quad (11)$$

Although the values of wear scar diameters measured (WSD) in the tests may appear relatively high for diesel fuels, it is important to emphasize that these results were obtained by means of a BOCLE [46], a piece of equipment established for kerosene fuels. In this sense, despite the wear scar diameter (WSD) values being higher than 460 μm (limit established in EN 590), the lubricity values of the fuels to be used in the diesel injector are considered acceptable because some studies have corroborated that the BOCLE methodology overesti-

mates WSD compared with the High Frequency Reciprocating Rig (HFRR) [49], equipment which is used in standard EN 590 to evaluate the lubricity of diesel fuels [50].

2.4. Test Matrix

To evaluate the effect of the fuel selected on the fuel injection process, a matrix with different values of injection pressure and fuel temperature was proposed for the experimental tests. Information about test conditions is detailed in Table 3. Each injection pressure was tested at each fuel temperature.

Table 3. Test conditions.

	Experimental Conditions	Unit
Nozzle diameter (d_o)	130	μm
Injection pressure (P_{rail})	50, 70, 90, 110	MPa
Fuel temperature (T)	293, 303, 313	K
Back pressure (P_{back})	5	MPa
Injector energizing time (ET)	2	ms
Number of injections	1	-
Number of repetitions	6	-

In this work a solenoid fuel injector was used. This was equipped with a convergent conical single-hole axial nozzle with a K-factor of 3.5. This was used to minimize cavitation phenomena inside the nozzle [51]. Appendix A presents, as an example, results of measurements made during the tests using Jet A-1 and the Jet A-1 + SPK-FT blend (DCN = 51) as representative cases.

Based on the proposed test plan, the effect of injection pressure and temperature on the total injected fuel mass was evaluated, along with the behavior of the fuel injection rate, current pulse of the injector, and discharge coefficient for the different fuels under controlled operating conditions. In addition, the density and viscosity of the neat fuels and blends were characterized by a range of temperatures to provide a comprehensive understanding of their physicochemical properties and their influence on injection performance.

3. Results and Discussion

3.1. Fuel Density and Viscosity

The evaluation of the effect of temperature on the density and viscosity of the tested fuels is necessary to calculate some parameters related to the fuel injection process. Figure 3 illustrates the variation in the measured density and viscosity of the tested fuels and blends for the selected temperature range. Different repetitions were carried out with each sample, two measurements for the density tests and three for viscosity, with the average values being presented (for each test condition and fuel) in Figure 3. Repetitiveness, included as error bars in Figure 3, was estimated as the standard deviation of these repetitions, being lower than 1 kg/m^3 for density results and lower than 0.02 cSt for kinematic viscosity ones. The measurement error associated with each instrument used has been considered in the error bars. Appendix B presents, as an example, results of a statistical analysis and uncertainty estimations for these properties, using Jet A-1 and Jet A-1 + SPK-FT fuel blend (DCN = 51) as representative cases.

As shown in Figure 3, both viscosity and density exhibit an almost linear trend in the studied temperature range. Diesel fuel displays the highest density and viscosity among the tested fuels. When comparing Jet A1 with its blends containing HVO or SPK-FT fuels, the density values are very similar, whereas viscosity differs. Interestingly, comparing Jet A1 with SPK-FT reveals that, despite SPK-FT having a lower density, its viscosity is

higher than that of conventional Jet A1. This behavior can be attributed to the molecular structure of paraffinic fuels: the high linearity of alkanes in SPK-FT promotes stronger van der Waals interactions, while low branching and the presence of long carbon chains increase intermolecular friction, all contributing to higher resistance to flow compared to the more branched and cyclic hydrocarbons present in Jet A1. These findings underscore the critical role of molecular linearity in shaping the viscosity and flow characteristics of paraffinic aviation fuels, as previously reported in studies correlating fuel composition and molecular structure with physicochemical properties such as viscosity, density, and net heat of combustion [52].

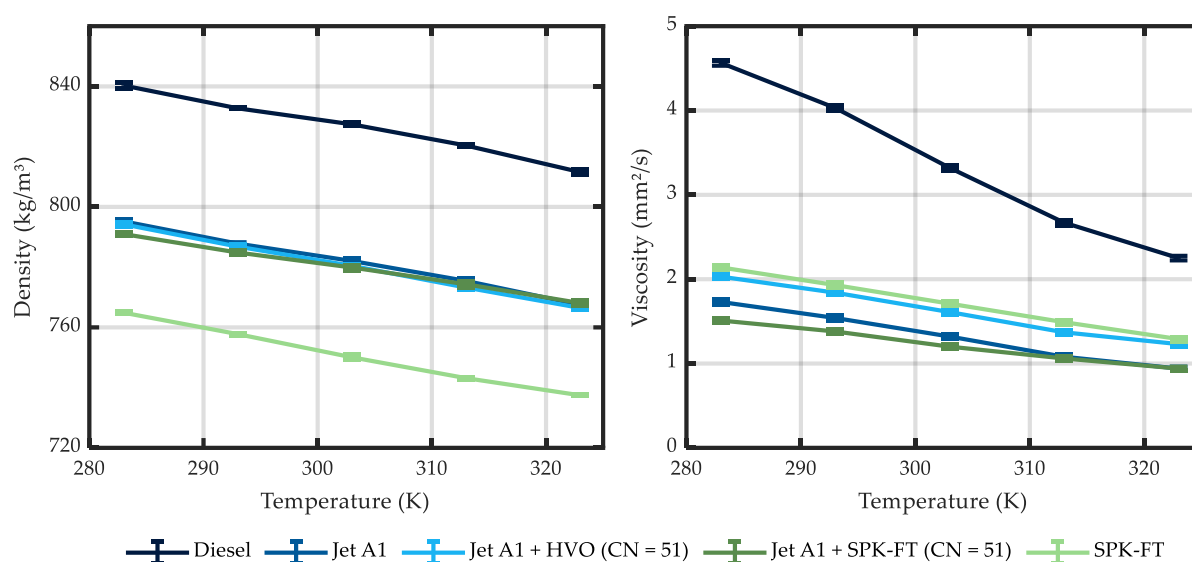


Figure 3. Density and viscosity of the tested fuels.

3.2. Fuel Injection Rate Measured

To evaluate the repetitiveness of values obtained during the measure of the different parameters studied, six repetitions ($n = 6$) were carried during each operating condition. The uncertainty associated with each data point was quantified by calculating the standard deviation. Figure 4 shows, as example, the dispersion of the mass flow rate and pulse for Jet A1 at an injection pressure of 90 MPa and a fuel temperature of 303 K.

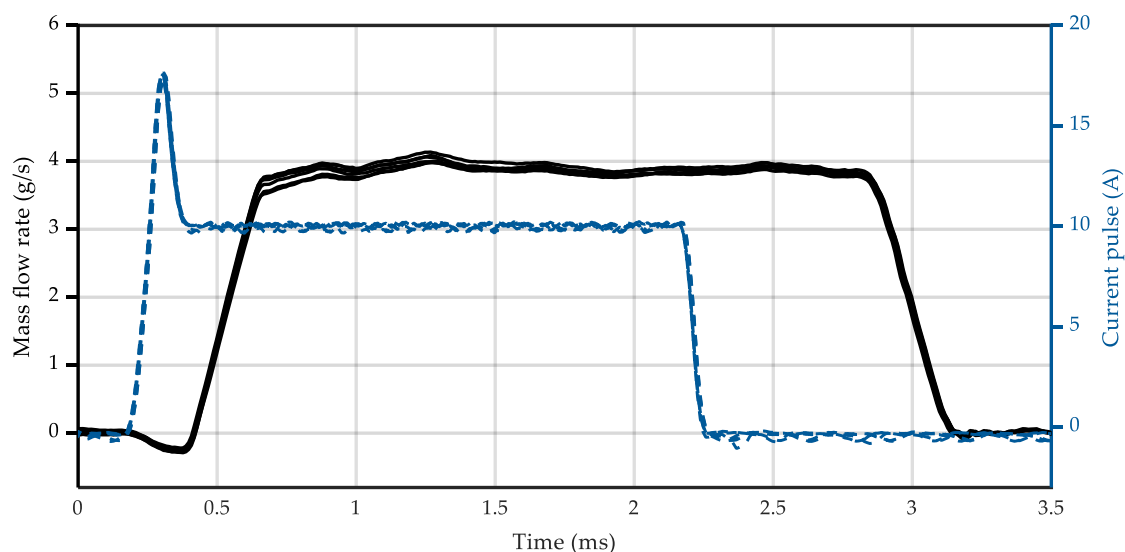


Figure 4. Example of repeatability of the mass flow rate and current pulse of the injector for Jet A1 (d_o : 130 μm , T : 303 K, P_{rail} : 90 MPa, P_{back} : 5 MPa, ET : 2 ms, n : 6).

To validate the reliability of the EVI-2-integrated mass (actual mass flow rate), these values were compared with rates estimated from gravimetric measurements on a balance. The comparison between the two methods provided a correlation coefficient greater than 0.9, confirming the consistency and accuracy of the experimental results. Figure 5 shows the slope, intercept, RMSE, and sample size for the correlation between the EVI-2-integrated mass and the balance-measured mass (with $R > 0.9$), along with a small scatter plot illustrating this correlation.

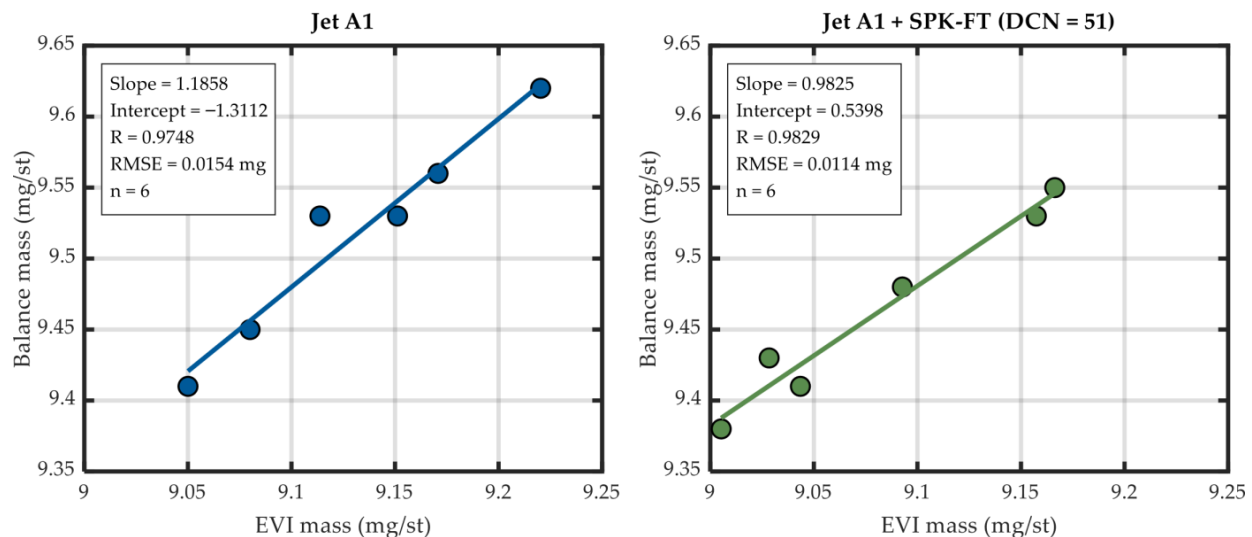


Figure 5. Correlation between the EVI-2-integrated mass and the balance-measured mass. (d_o : 130 μm , T : 303 K, P_{rail} : 90 MPa, P_{back} : 5 MPa, ET : 2 ms, n : 6).

Figure 6 shows an example of intermediate experimental results of the injection rate obtained using Jet A1. From the measured mass flow rate, the total injected fuel mass was determined. Furthermore, by analyzing the current pulse and the mass flow rate signal, the hydraulic injection delay (HID) and duration of injection (DoI) were estimated. Finally, the discharge coefficient was calculated considering the experimental data corresponding to the average rail pressure (P_{rail}) during the period of the injection process and the measured average back pressure (P_{back}). Appendix B presents, for example, results of the statistical analysis and uncertainty estimation for these variables, using Jet A-1 and Jet A-1 + SPK-FT blend (DCN = 51) as representative cases.

The injection rate profiles of the studied fuels under the different operating conditions tested are presented below. The presented evolution of mass flow rate for each fuel corresponds to the mean value of six repetitions, and the error bars were calculated as the standard deviation.

According to Figures 7–9, a common expected trend is observed among the fuels: greater injection pressure leads to greater mass flow rate. Moreover, when comparing the behavior of the different fuels under identical operating conditions, it can be observed that aviation fuels, both conventional and sustainable, exhibit slightly lower injection rates compared to diesel fuel.

Analyzing the injection rate profiles of the different fuels at 50 MPa and temperatures of 303 K and 313 K (Figures 8 and 9), diesel exhibits a slight delay in the start of injection, which becomes more pronounced as temperature increases, even though its cetane number is higher than that of Jet A1.

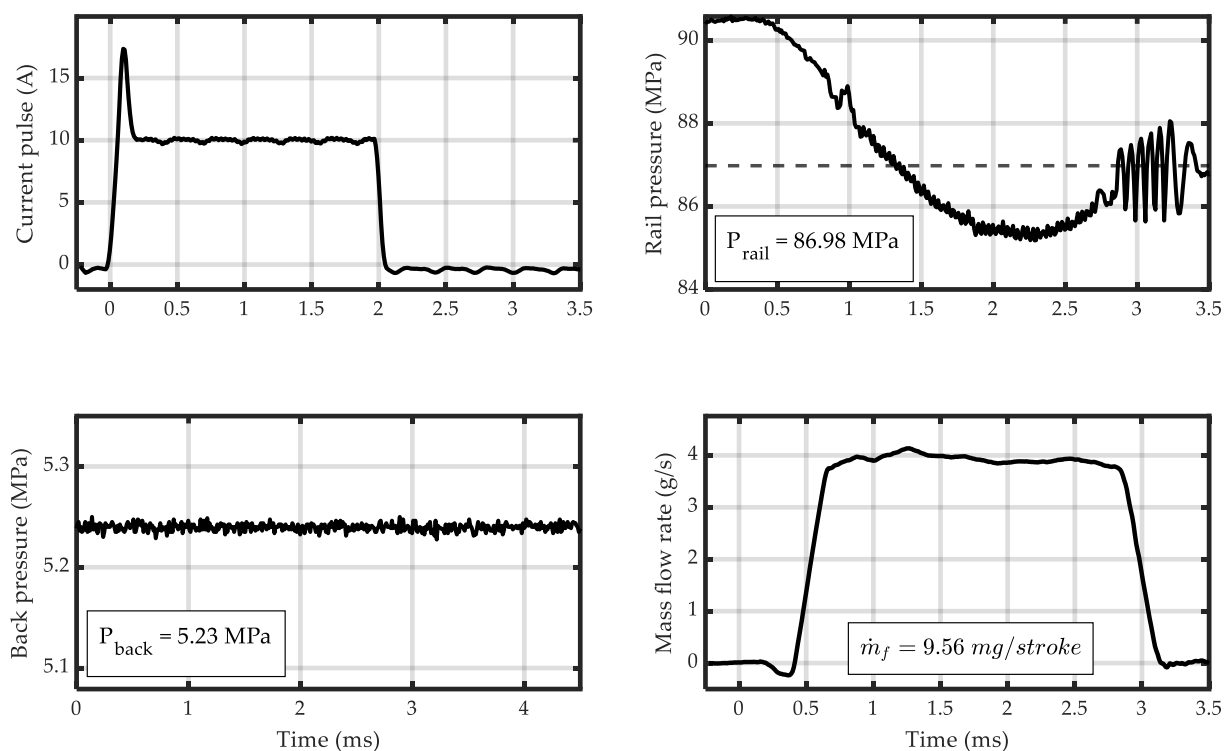


Figure 6. Example of intermediate experimental results of the fuel injection rate obtained using Jet A1. (do : 130 μm , T : 303 K, P_{rail} : 90 MPa, P_{back} : 5 MPa, ET : 2 ms, n : 1).

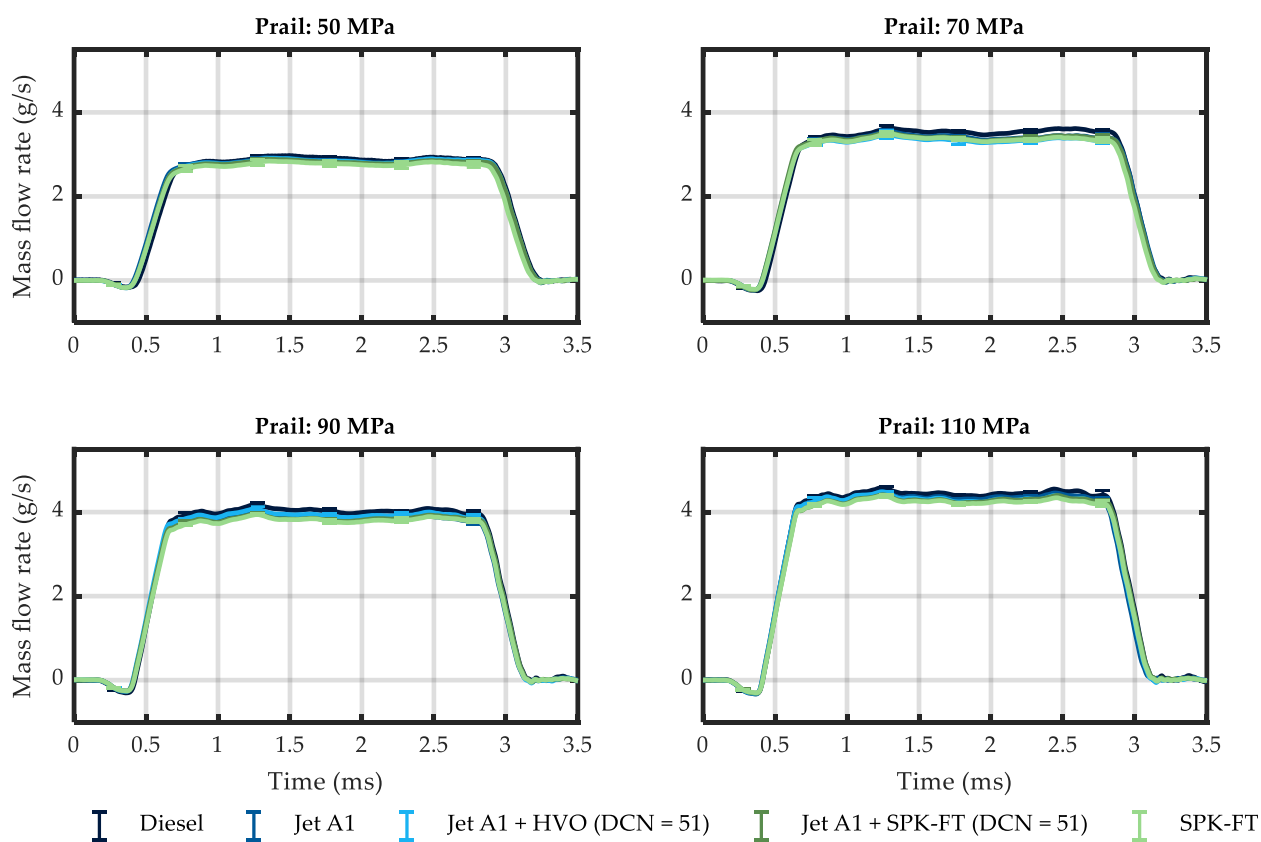


Figure 7. Fuel injection rates determined under different injection pressures at constant fuel temperature (do : 130 μm , T : 293 K, P_{back} : 5 MPa, ET : 2 ms, n : 6).

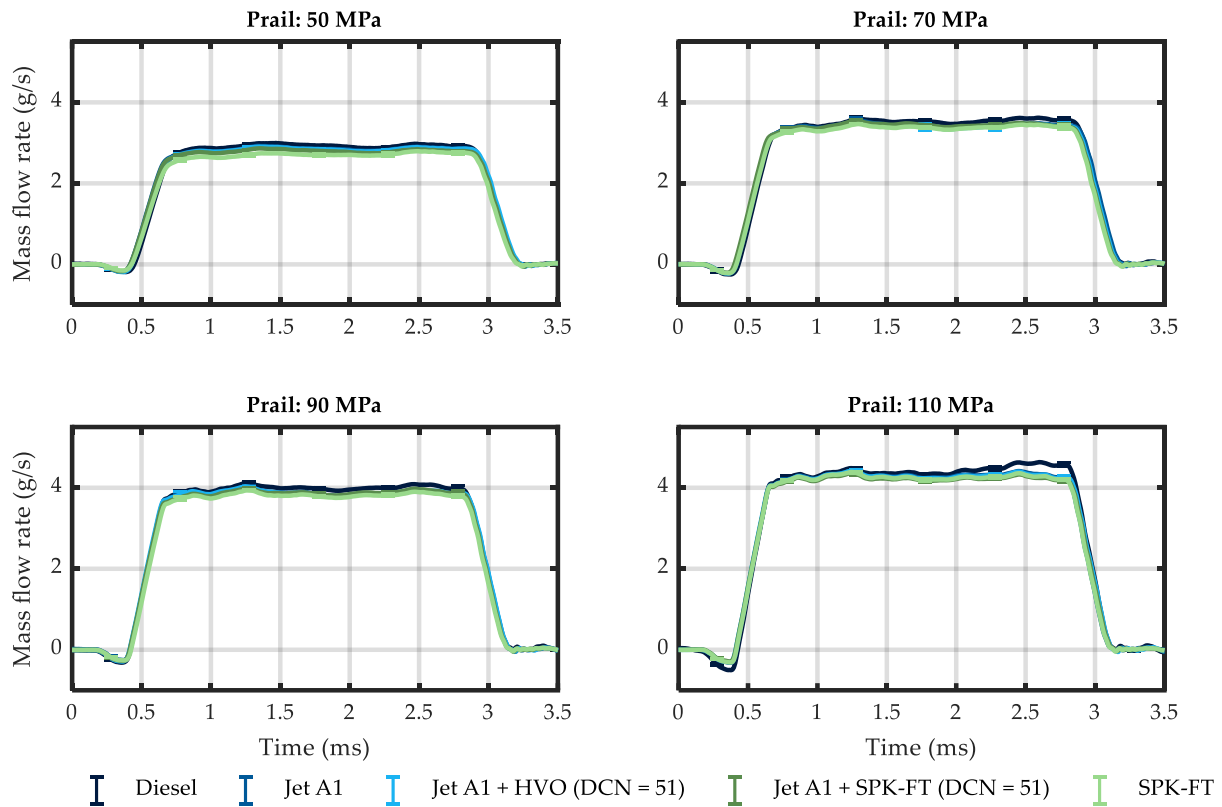


Figure 8. Fuel injection rates under different injection pressures at constant fuel temperature (d_o : 130 μm , T : 303 K, P_{back} : 5 MPa, ET : 2 ms, n : 6).

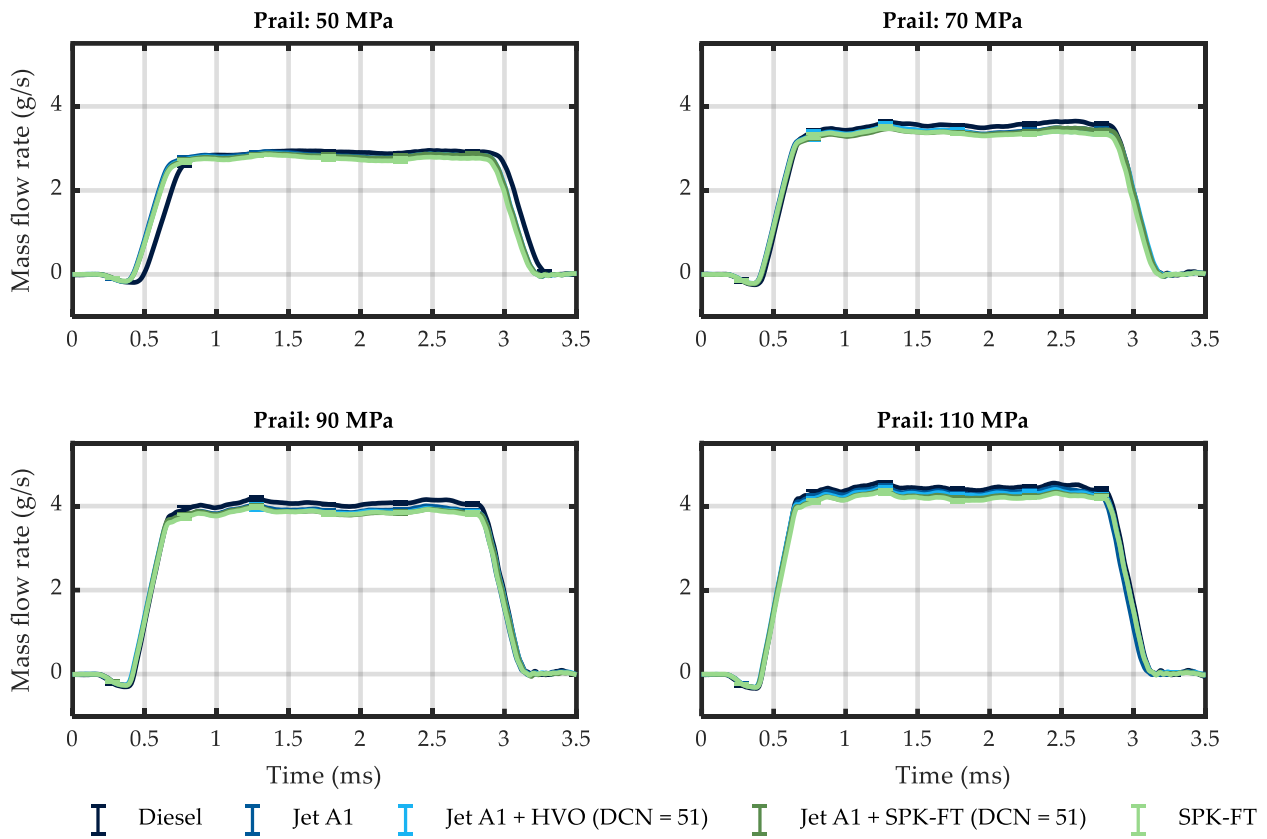


Figure 9. Fuel injection rates under different injection pressures at constant fuel temperature (d_o : 130 μm , T : 313 K, P_{back} : 5 MPa, ET : 2 ms, n : 6).

3.3. Injection Delay and Duration

The curves of mass flow rate and current pulse of the injector corresponding to Jet A1 are shown in Figure 10 as an example, where the hydraulic injection delay and delay of injection are presented.

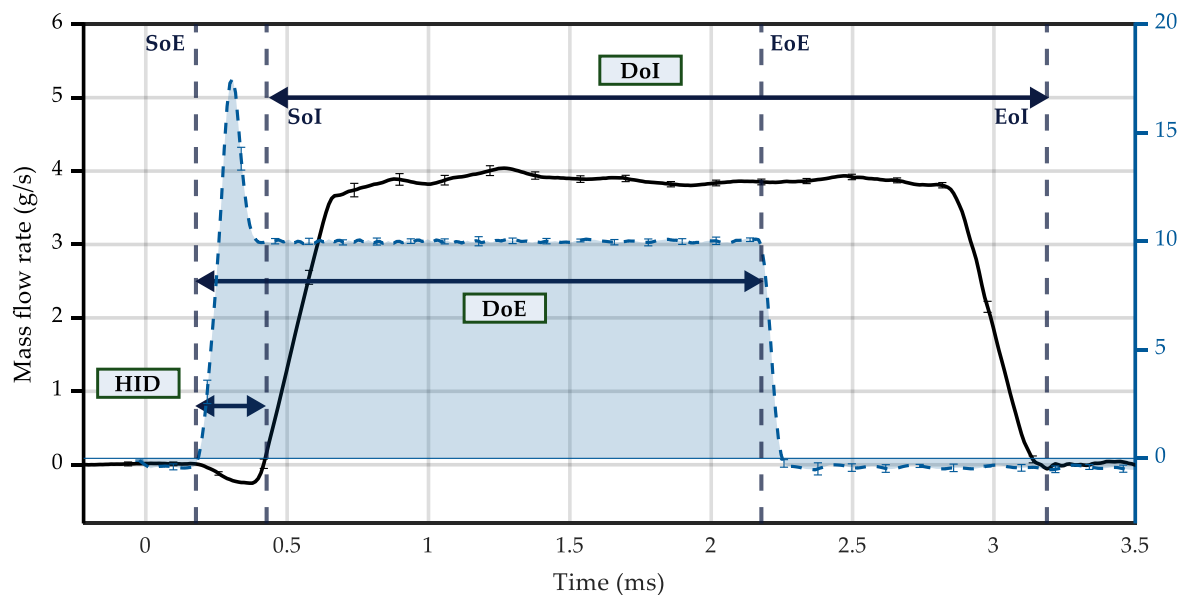


Figure 10. Example of hydraulic injection delay (HID), duration of energizing (DoE), and duration of injection (DoI) using Jet A1 fuel (do : 130 μm , T : 303 K, P_{rail} : 90 MPa, P_{back} : 5 MPa, ET : 2 ms).

The hydraulic injection delay (HID) was determined as the time difference between the start of energizing (SoE), when the injector receives the activation signal, and the start of injection (SoI), when the fuel begins to flow through the nozzle.

Conversely, the duration of injection (DoI) was obtained by measuring the time interval between the start of injection (SoI) and the end of injection (EoI), when the fuel flow ceases.

The scheme above shows a hypothetical mass flow rate signal and graphically explains the procedure to determine the start and end of injection (SoI and EoI). A similar method is used to find the start of energizing (SoE) from the injector current signal. The end of energizing (EoE) corresponds to the upper end of the descending slope of the current signal (see Figure 11).

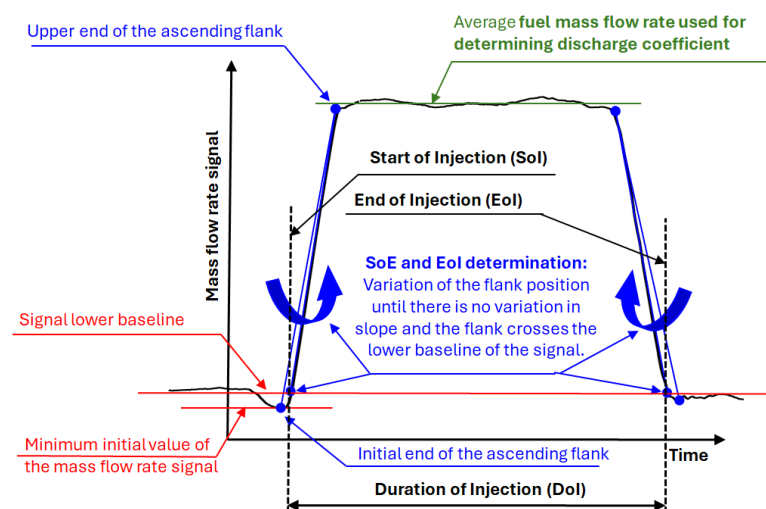


Figure 11. Scheme of the mass flow rate signal illustrating the method to determine the start and end of injection (SoI and EoI) based on flank position and signal baselines.

Figure 12 presents the effect of injection pressure at different constant fuel temperatures on the HID. In general, increasing the injection pressure from 50 to 70 MPa reduces the delay for all fuels. While diesel fuel shows a slight decrease in the hydraulic injection delay as the injection pressure increases to 90 and 110 MPa, the rest of the fuels exhibit an almost constant behavior beyond 70 MPa, with very little variation among them. At the lowest injection pressure (50 MPa), a more noticeable difference can be observed between diesel and kerosene fuels or their blends. This result is justified, at low pressures, by the fact that the behavior of diesel is primarily governed by its rheological properties. However, as the pressure increases, the pressure gradient becomes the dominant factor, gradually diminishing the influence of density and viscosity and, consequently, the system's sensitivity to these fuel characteristics. Under these low-pressure conditions, higher temperatures further contribute to an extended hydraulic injection delay. This phenomenon could be related to the compressibility of diesel fuel compared to other fuels tested over the studied temperature range. Probably, part of the hydraulic energy is dissipated in compressing the fluid before the injector needle opens, thereby prolonging the system's response time and delaying the start of injection. Another factor that could also explain this behavior may be associated with the fuel's fugacity.

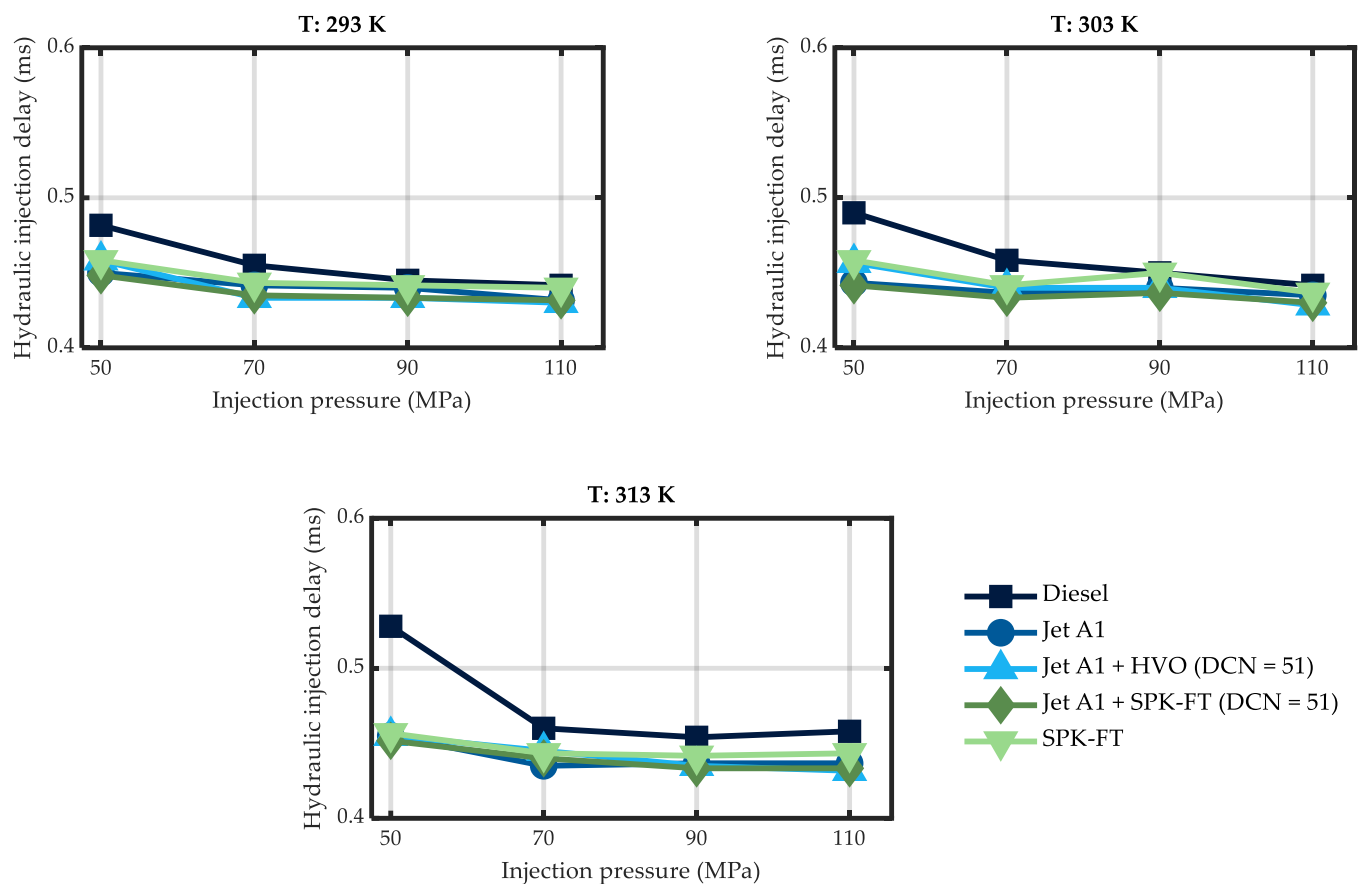


Figure 12. Hydraulic injection delay vs. injection pressure at different temperatures (d_o : 130 μm , P_{back} : 5 MPa, ET : 2 ms).

In contrast, aviation fuels and their blends exhibit almost the same hydraulic injection delay under identical operating conditions. Furthermore, the hydraulic injection delay remains nearly constant for these fuels as temperature varies, indicating consistent hydraulic behavior and stable injector performance across the evaluated temperature range.

Like Figure 12, the results of injection duration for fuels tested under the injection pressures and temperatures selected for these tests are plotted in Figure 13. Values obtained

for different fuels were similar, remaining unaffected by both injection pressure and fuel temperature within the studied range.

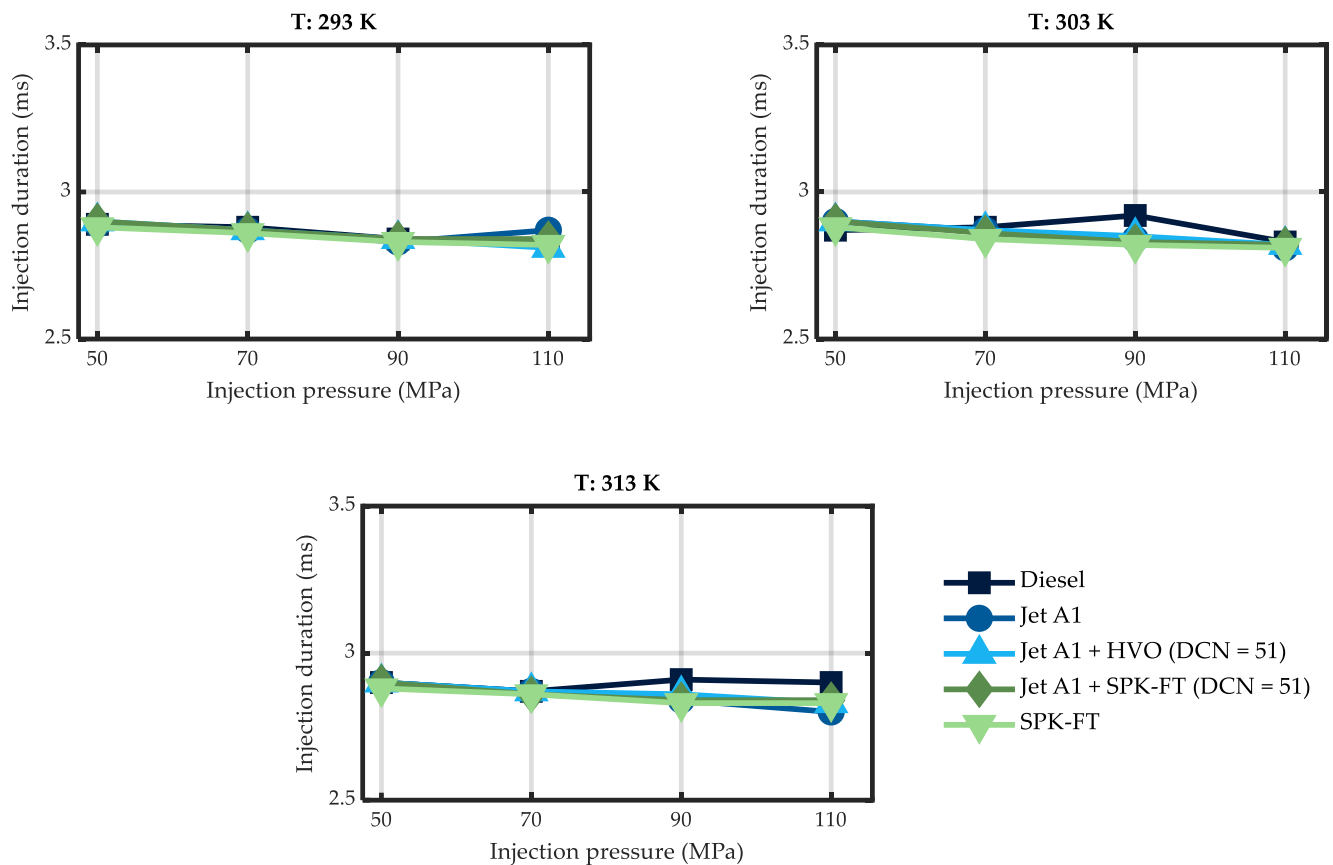


Figure 13. Injection duration vs. injection pressure at different temperatures (d_o : 130 μm , P_{back} : 5 MPa, ET : 2 ms).

3.4. Total Injected Fuel Mass

Figure 14 illustrates the effect of injection pressure on the total injected fuel mass at each temperature studied. The analysis confirms the previously observed trend in the mass flow rate: kerosene neat fuels and blends exhibit a lower total injected mass compared to diesel fuel. This behavior can be attributed to the rheological properties of kerosene, which are characterized by lower density and viscosity than diesel fuel (Figure 3). These properties reduce the sealing capability within the tolerances of the injection system, leading to higher return losses and a consequent decrease in the effective pressure at the nozzle outlet. As a result, the total injected mass is lower. The differences in mass injected with kerosene fuels grow larger as the injection pressure increases, especially when SPK-FT is used. Comparing both kerosene fuels with diesel, the mean reductions obtained (considering values obtained at different pressure and temperature conditions) are higher with neat SPK-FT and its blend ($\sim 4.7\%$ and 3.3% , respectively) than those corresponding to neat Jet A1 and its blend ($\sim 2.5\%$).

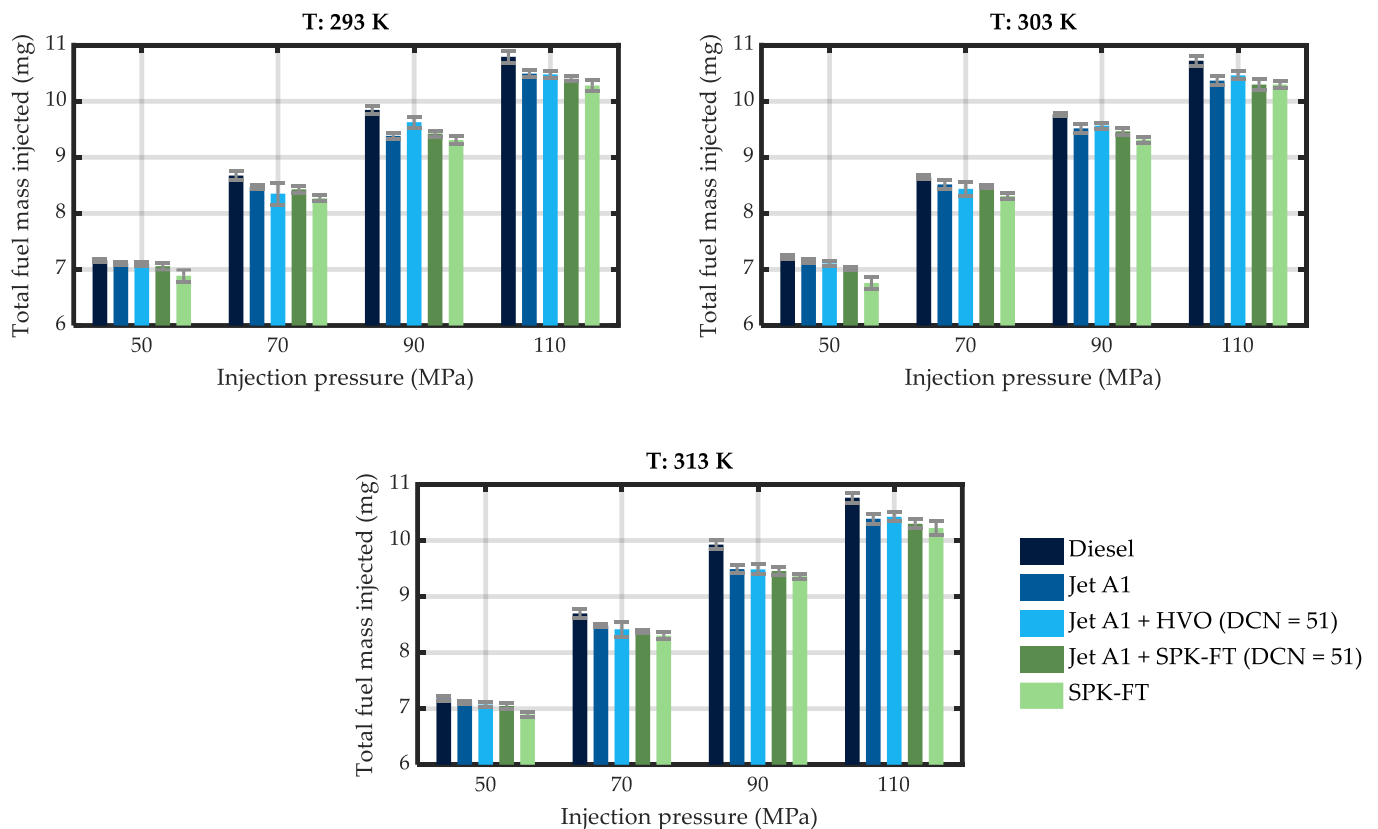


Figure 14. Total fuel injected mass under different injection pressures at different fuel temperatures (do: 130 μm , P_{back} : 5 MPa, ET : 2 ms).

When comparing Jet A1 and its blends with HVO or SPK-FT, in some cases, the former exhibited higher injection rates. This difference can be attributed to a combination of factors: the lower density of SPK-FT reduces the mass transferred per unit volume, while its higher viscosity increases frictional losses in the conduits and affects the needle dynamics, thereby reducing the effective area and discharge coefficient. Additionally, variations in surface and lubricity properties may have an influence on cavitation and internal leakage, collectively contributing to a net reduction in the injection rate. Consequently, overall, Jet A1 and its blend with HVO demonstrate more favorable injection performance than their renewable counterpart (SPK-FT).

The disadvantage of neat kerosene fuels and their blends, compared to diesel fuel, becomes more evident at higher injection pressures. Their lower density and viscosity lead to greater internal losses and a lower stable flow, limiting their ability to effectively exploit the available pressure gradient. As a result, kerosene fuels and blends exhibit lower injection rates under high-pressure conditions, highlighting their sensitivity to both rheological properties and pressure-dependent operating regimes.

Figure 15 illustrates the effect of temperature on the total fuel mass injected at each injection pressure condition tested, demonstrating that temperature plays an insignificant role in the performance of the fuels under the tested conditions.

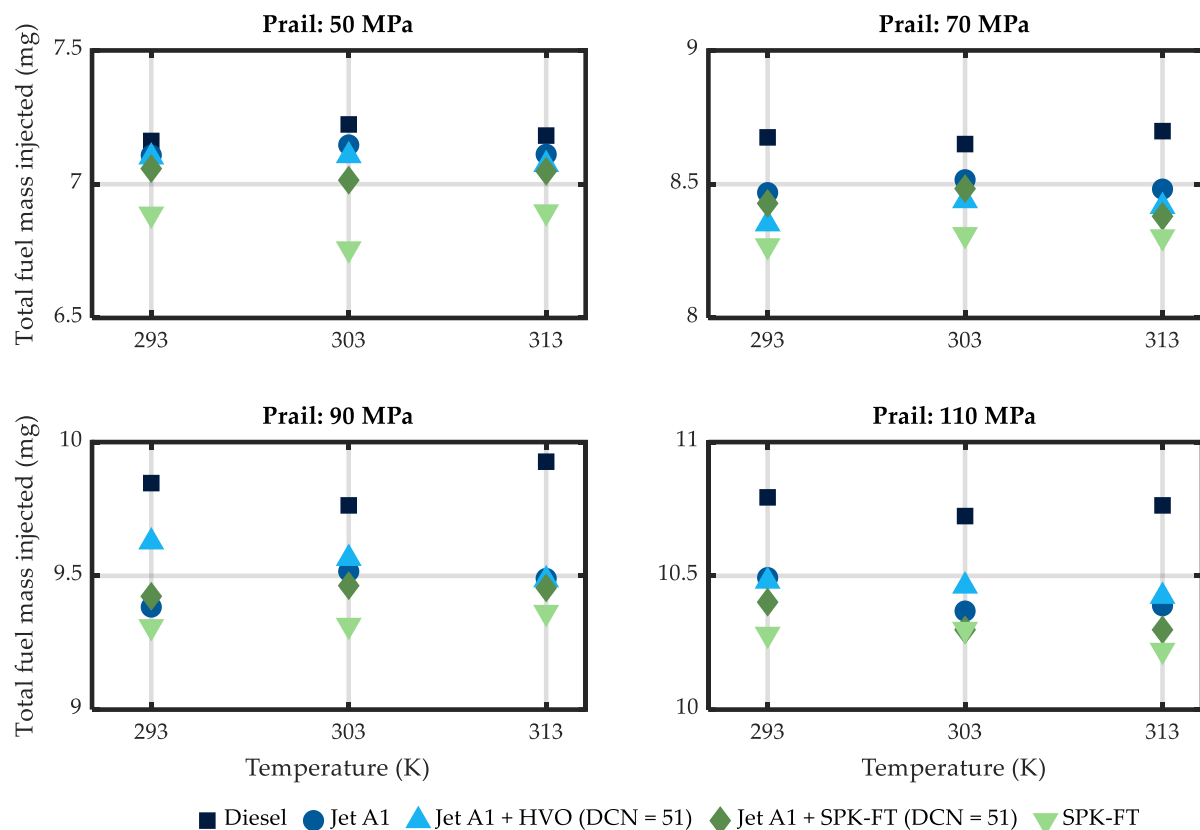


Figure 15. Total injected fuel mass under different constant fuel temperatures at each constant injection pressure tested (d_o : 130 μm , P_{back} : 5 MPa, ET : 2 ms).

3.5. Nozzle Discharge Coefficient

Results of discharge coefficient versus injection pressure for different fuels tested at each temperature are presented in Figure 16. Similarly to injection duration, the effects of injection pressure and temperature are almost negligible on the discharge coefficient. Appendix C presents, as an example, the results of uncertainty propagation for C_d in Jet A1 and the blend Jet A1 + SPK-FT (DCN = 51) as representative cases.

Figure 17 shows that the discharge coefficient remains nearly constant for all fuels across the tested temperatures (293 K, 303 K, and 313 K), as the Reynolds number increases. Each set of points corresponds to injection pressures of 50, 70, 90, and 110 MPa. The increase in pressure raises the Reynolds number by enhancing flow velocity, but this has no significant effect on C_d , indicating a fully turbulent regime where C_d stabilizes. Moreover, the similar behavior among fuels suggests that small differences in density and viscosity do not noticeably affect the hydraulic performance of the injector orifice. Overall, the results confirm that within the studied range, both temperature and pressure exert negligible influences on the discharge coefficient. The lowest Re number of diesel fuel can be mainly explained by its higher viscosity compared to aviation kerosene.

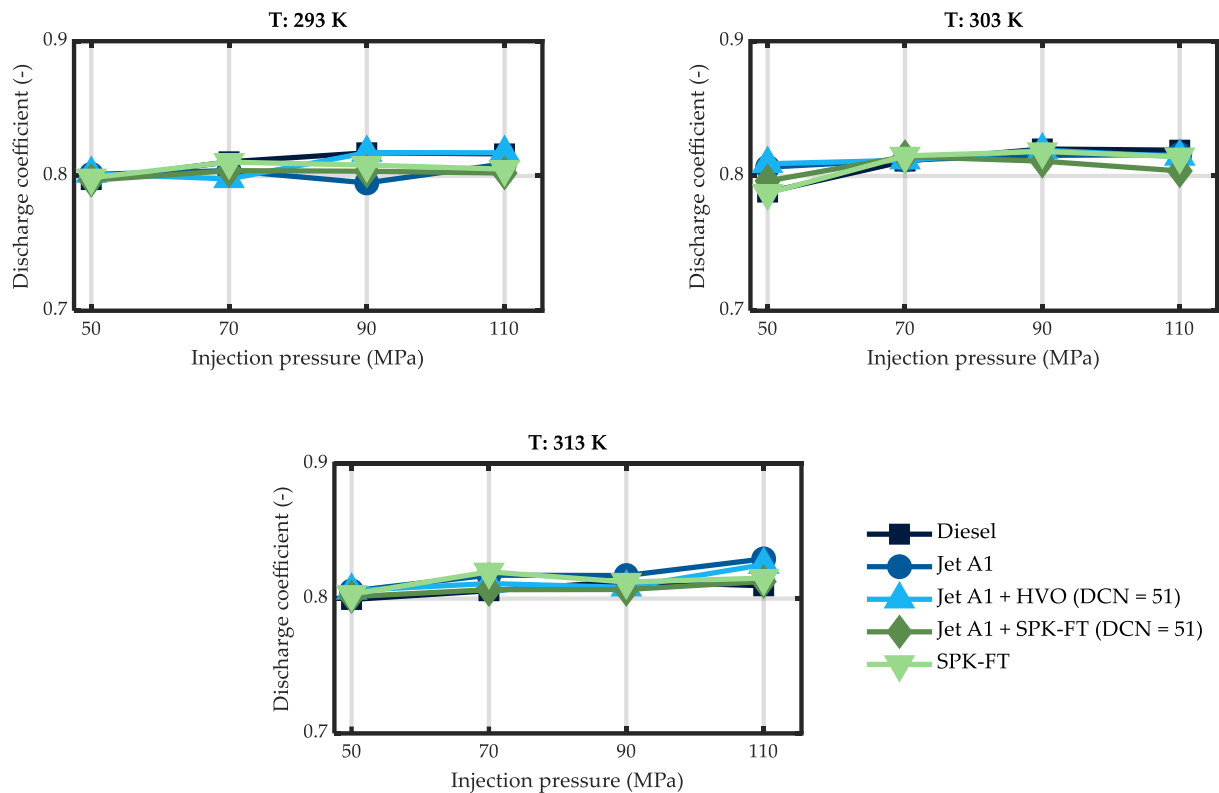


Figure 16. Discharge coefficient vs. injection pressure on the nozzle at different temperatures (d_o : 130 μm , P_{back} : 5 MPa, ET : 2 ms).

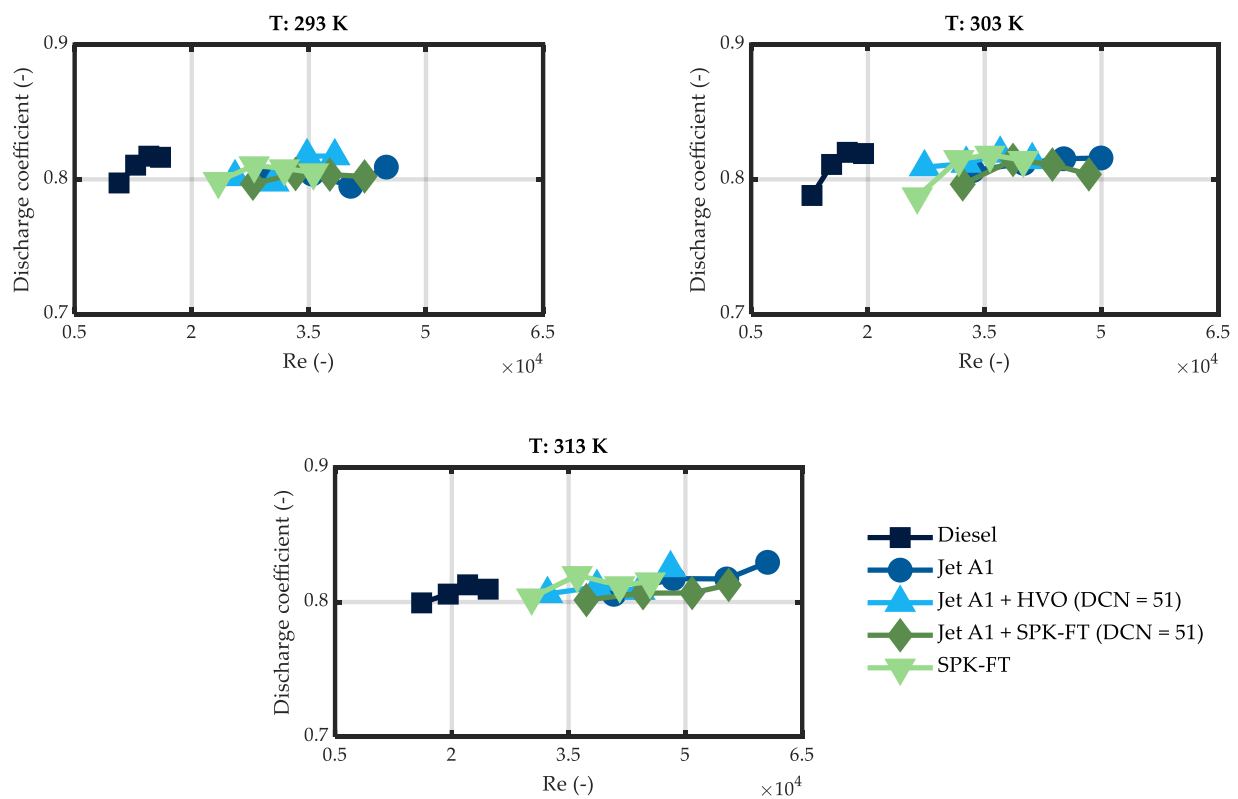


Figure 17. Impact of Reynolds number on the nozzle discharge coefficient (d_o : 130 μm , P_{back} : 5 MPa, ET : 2 ms).

3.6. Fuel Mass, Volume, and Energy Injected

The influence of injection pressure on the total injected mass, released energy, and injected volume for the different fuels tested, under set values of temperature (303 K) and energization time (2 ms), are presented in Figure 18. For the three parameters evaluated, an increasing trend with injection pressure is observed, consistent with the expected hydraulic behavior of a common-rail injection system.

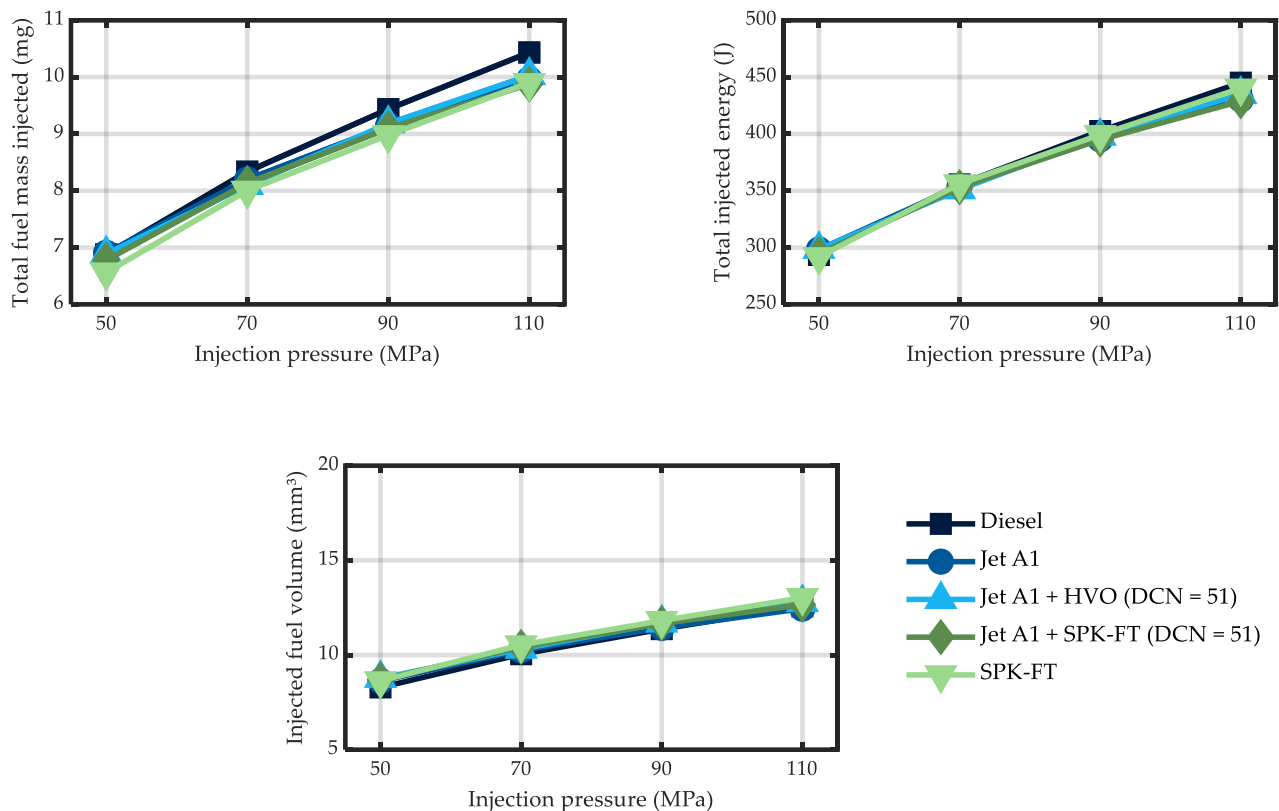


Figure 18. Total mass injected, volume injected, and released energy vs. injection pressure for the different fuels tested (d_o : 130 μm , T : 303 K, P_{back} : 5 MPa, ET : 2 ms).

Although diesel fuel exhibits a slightly higher total injected mass, the differences being higher as the injection pressure increases, the differences among the analyzed fuels can be considered minimal across the entire pressure range, both in terms of injected mass and total injected energy. Similar results of injected energy between fuels indicate that the disadvantage (a priori) associated with kerosene blends in terms of lower mass injected (~5%) is compensated for by their higher mass heating value (~3.6%). Consequently, the total energy injected per cycle remains practically constant. Results obtained in the injected volume show similar trends, consistent with the small differences in density between paraffinic fuels and fossil diesel fuel. Appendix D presents, as an illustrative example, results of the injected-energy calculation (injected mass $\times$ LHV) for a representative temperature and the four injection pressures evaluated, supporting the discussion of energy-per-shot parity across the tested fuels.

Overall, the results indicate that the hydraulic and injection behaviors of the system are barely affected by fuel substitution, demonstrating full operational compatibility between conventional diesel fuel and the tested neat kerosene fuels and their blends, while maintaining equivalent energy performance under the evaluated conditions.

4. Conclusions

The effect of neat kerosene fuels, one fossil and the other sustainable, and their blends on the characteristic parameters of the injection process were evaluated. These results were compared to a diesel fuel (reference one in compression ignition engine) and a blend of the fossil aviation fuel (Jet A1) with a renewable diesel fuel (HVO). Tests were carried out under different injection pressures and temperatures, using an experimental setup developed to determine the injection rate in a common-rail system, primarily with a solenoid injector but also adaptable to piezoelectric types. From the experimental results, the following conclusions were drawn:

- Fuel rheological properties are critical in determining the performance of the injection system.
- Based on the error propagation and uncertainty analysis, it can be concluded that the acquired data are both reproducible and reliable. The evaluation confirms a high level of experimental quality and strong confidence in the results presented.
- Raising the injection pressure from 50 to 70 MPa reduces the hydraulic injection delay for all fuels. Under low-pressure tests, an increase in hydraulic injection delay with diesel fuel is observed, mainly at the highest temperature.
- All fuels exhibit the same injection duration under all tested conditions, showing no significant influence of pressure or temperature.
- Discharge coefficient is nearly constant for all fuels, temperatures, and pressures, showing negligible influence of operating conditions on injector performance.
- The uncertainty propagation analysis for the discharge coefficient shows that, according to the sensitivity assessment, pressure variation is the parameter that contributes the most to the overall uncertainty.
- With all fuels tested, the injected mass grows consistently with increasing injection pressure, while the effect of fuel temperature can be considered negligible across the evaluated temperature range.
- Fossil kerosene fuel shows a lower fuel mass injected than diesel fuel, with the disparity increasing at higher injection pressures. Jet A-1 and its blend with HVO and SPK-FT exhibit a higher mass injected than SPK-FT, outperforming their sustainable counterpart due to differences in density and viscosity.
- Similar results of injected energy between fuels indicate that the disadvantage (a priori) associated with kerosene blends, in terms of lower mass injected (~5%), is compensated for by their higher mass heating value (~3.6%).
- Similar enough hydraulic behaviors during the injection process were obtained, confirming an acceptable operational compatibility and equivalent performance within the common-rail injection system.

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Nomenclature

ANN	Artificial Neural Network
C_d	Discharge coefficient
CV	Coefficient of Variation
DCN	Derived cetane number
DoE	Duration of energizing
DoI	Duration of injection
d_o	Nozzle diameter
EoE	End of energizing
EoI	End of injection
ET	Injector energizing time
GSE	Ground support equipment
HID	Hydraulic injection delay
HVO	Hydrotreated Vegetable Oil
n	Number of repetitions
$\dot{m}_f$	Actual fuel mass flow rate
$\dot{m}_{f_{th}}$	Theoretical fuel mass flow rate
P_{rail}	Common-rail injection pressure
P_{back}	Back pressure
Re	Reynold number
SAF	Sustainable Aviation Fuel
SD	Standard deviation
SFC	Single Fuel Concept
SPK-FT	Fischer–Tropsch Synthetic Paraffinic Kerosene
SoE	Start of energizing
SoI	Start of injection
UAV	Unmanned aerial vehicles

Appendix A. T-Test for Jet A1 and Blend Jet A1 + SPK-FT (DCN = 51)

Table A1. Example of T-test for Jet A1.

Fuel	Repetition	P_{rail} (MPa)	T (K)	T_{test} (K)	T_{EVI} (K)	ρ_f ($\frac{kg}{s}$)	μ_f (cSt)	$\dot{m}_f$ ($\frac{g}{s}$)	DCN	%Biod.
Jet A1	1	90	293	294.1	311.6	788	1.54	9.36	43.95	2
	2	90	293	294.2	311.8	788	1.54	9.4	43.95	2
	3	90	293	294.3	311.8	788	1.54	9.35	43.95	2
	4	90	293	294.4	312.1	788	1.54	9.48	43.95	2
	5	90	293	293.6	312.2	788	1.54	9.33	43.95	2
	6	90	293	293.9	312.4	788	1.54	9.38	43.95	2
	1	90	303	304.6	308.8	782	1.32	9.56	43.95	2
	2	90	303	304.8	308.9	782	1.32	9.53	43.95	2
	3	90	303	304.2	309.2	782	1.32	9.41	43.95	2
	4	90	303	303.8	309.2	782	1.32	9.53	43.95	2

Table A1. Cont.

Fuel	Repetition	Prail (MPa)	T (K)	Ttest (K)	T EVI (K)	$\rho_f (\frac{kg}{s})$	$\mu_f (cSt)$	$\dot{m}_f (\frac{g}{s})$	DCN	%Biod.
Jet A1	5	90	303	303.6	309.4	782	1.32	9.45	43.95	2
	6	90	303	303.7	309.5	782	1.32	9.62	43.95	2
	1	90	313	313.4	312.8	775	1.08	9.56	43.95	2
	2	90	313	312.6	313	775	1.08	9.56	43.95	2
	3	90	313	312.8	313.1	775	1.08	9.48	43.95	2
	4	90	313	313	313.3	775	1.08	9.4	43.95	2
	5	90	313	313.8	313.4	775	1.08	9.51	43.95	2
	6	90	313	312.8	313.4	775	1.08	9.43	43.95	2

Test conditions: Fuel: Jet A1, do: 130 μm , P_{rail} : 90 MPa, P_{back} : 5 MPa, ET: 2 ms, n: 6.

Table A2. Example of T-test for the blend Jet A1 + SPK-FT (DCN = 51).

Fuel	Repetition	Prail (MPa)	T (K)	Ttest (K)	T EVI (K)	$\rho_f (\frac{kg}{s})$	$\mu_f (cSt)$	$\dot{m}_f (\frac{g}{s})$	DCN	%Biod.
Jet A1 + SPK-FT (DCN = 51)	1	90	293	294.9	310.7	785	1.38	9.35	51	2
	2	90	293	295	310.8	785	1.38	9.43	51	2
	3	90	293	294.5	310.8	785	1.38	9.4	51	2
	4	90	293	294.5	311	785	1.38	9.46	51	2
	5	90	293	294.1	311.3	785	1.38	9.5	51	2
	6	90	293	293.6	311.3	785	1.38	9.4	51	2
	1	90	303	303.5	312.8	780	1.20	9.53	51	2
	2	90	303	304	312.8	780	1.20	9.43	51	2
	3	90	303	304	312.9	780	1.20	9.41	51	2
	4	90	303	303.4	313	780	1.20	9.55	51	2
	5	90	303	303	312.9	780	1.20	9.48	51	2
	6	90	303	302.9	313	780	1.20	9.38	51	2
	1	90	313	314	309.7	774	1.06	9.55	51	2
	2	90	313	312.9	310	774	1.06	9.5	51	2
	3	90	313	312.5	310	774	1.06	9.48	51	2
	4	90	313	313.2	310.1	774	1.06	9.46	51	2
	5	90	313	312.7	310.2	774	1.06	9.38	51	2
	6	90	313	314.8	310.2	774	1.06	9.36	51	2

Test conditions: do: 130 μm , P_{rail} : 90 MPa, P_{back} : 5 MPa, ET: 2 ms, n: 6.

Appendix B. Example of Statistics and Uncertainty of Independent Variables for Jet A1 and Blend Jet A1 + SPK-FT (DCN = 51)

Table A3. Statistics and uncertainty of independent variables for Jet A1.

Repetition	Prail (MPa)	Pback (MPa)	Current Pulse (A)	$\dot{m}_f (\frac{g}{s})$	$\rho_f (\frac{kg}{s})$	$\mu_f (cSt)$
1	86.067	5.236	9.9996	3.886	782	1.08
2	89.573	5.235	9.9894	3.891	782	1.07
3	88.394	5.234	10.0030	3.834	-	1.08
4	85.562	5.239	9.9974	3.870	-	-
5	87.018	5.240	9.9954	3.864	-	-
6	88.021	5.240	9.9993	3.936	-	-
Mean	87.439	5.237	9.9974	3.880	782	1.08

Table A3. *Cont.*

Repetition	P_{rail} (MPa)	P_{back} (MPa)	Current Pulse (A)	$\dot{m}_f$ ($\frac{g}{s}$)	ρ_f ($\frac{kg}{s}$)	μ_f (cSt)
SD	1.509	0.0027	0.0046	0.034	-	0.006
CV	1.73%	0.05%	0.05%	0.87%	-	0.54%
Type A uncertainty	0.616	0.001	0.0019	0.014	-	0.003
Type B uncertainty	0.874	0.100	0.1500	0.017	1.000	0.003
Total uncertainty	1.070	0.100	0.1500	0.022	1.000	0.0046

Test conditions: d_o : 130 μ m, T : 303 K, P_{rail} : 90 MPa, P_{back} : 5 MPa, ET : 2 ms.

Table A4. Statistics and uncertainty of independent variables for the blend Jet A1 + SPK-FT (DCN = 51).

Repetition	P_{rail} (MPa)	P_{back} (MPa)	Current Pulse (A)	$\dot{m}_f$ ($\frac{g}{s}$)	ρ_f ($\frac{kg}{s}$)	μ_f (cSt)
1	88.383	4.993	9.9635	3.887	780	1.20
2	86.467	4.988	9.9749	3.855	780	1.20
3	89.760	4.990	9.9668	3.839	-	1.20
4	88.633	4.982	9.9616	3.904	-	-
5	88.444	4.964	9.952	3.871	-	-
6	87.736	4.961	9.9699	3.826	-	-
Mean	88.237	4.980	9.9648	3.864	780	1.20
SD	1.088	0.0140	0.0078	0.029	-	-
CV	1.23%	0.28%	0.08%	0.76%	-	-
Type A uncertainty	0.444	0.006	0.0032	0.012	-	-
Type B uncertainty	0.882	0.100	0.1495	0.017	1.000	0.0036
Total uncertainty (uT)	0.988	0.100	0.1495	0.021	1.000	0.0036

Test conditions: d_o : 130 μ m, T : 303 K, P_{rail} : 90 MPa, P_{back} : 5 MPa, ET : 2 ms.

Appendix C. Example of Uncertainty Propagation for C_d in Jet A1 and the Blend Jet A1 + SPK-FT (DCN = 51)

Table A5. Uncertainty propagation for C_d in Jet A1.

Variable (x)	$\dot{m}_f$ ($\frac{kg}{s}$)	A_{geom} (m^2)	ρ_f ($\frac{kg}{s}$)	ΔP (Pa)	C_d
Mean	3.880×10^{-3}	1.327×10^{-8}	782	8.220×10^7	0.82
Total uncertainty (uT)	2.213×10^{-5}	-	1	1.075×10^6	0.0071
Sensitivity $\partial C_d / \partial x$	210.118	0	-5.213×10^{-4}	-4.959×10^{-9}	-
Contribution $\left(\frac{\partial C_d}{\partial x} * uT\right)^2$	2.162×10^{-5}	0	2.717×10^{-7}	2.840×10^{-5}	5.029×10^{-5}
% Contribution	42.99%	0%	0.54%	56.46%	-

Test conditions: d_o : 130 μ m, T : 303 K, P_{rail} : 90 MPa, P_{back} : 5 MPa, ET : 2 ms, n : 6.

Table A6. Uncertainty propagation for C_d in the blend Jet A1 + SPK-FT (DCN = 51).

Variable (x)	$\dot{m}_f$ ($\frac{kg}{s}$)	A_{geom} (m^2)	ρ_f ($\frac{kg}{s}$)	ΔP (Pa)	C_d
Mean	3.864×10^{-3}	1.327×10^{-8}	780	8.326×10^7	0.81
Total uncertainty (uT)	2.108×10^{-5}	-	1	9.927×10^5	0.0065
Sensitivity $\partial C_d / \partial x$	209.050	0	-5.178×10^{-4}	-4.851×10^{-9}	-
Contribution $\left(\frac{\partial C_d}{\partial x} * uT\right)^2$	1.941×10^{-5}	0	2.681×10^{-7}	2.319×10^{-5}	4.287×10^{-5}
% Contribution	45.29%	0%	0.63%	54.09%	-

Test conditions: d_o : 130 μ m, T : 303 K, P_{rail} : 90 MPa, P_{back} : 5 MPa, ET : 2 ms, n : 6.

Appendix D. Supporting Calculations for Energy-per-Shot Parity Claim (Figure 17)

Table A7. Example of total fuel mass injected (mg) at different injection pressures tested.

Fuel	<i>Prail:50 MPa</i>	<i>Prail:70 MPa</i>	<i>Prail:90 MPa</i>	<i>Prail:110 MPa</i>
Diesel	6.88	8.34	9.44	10.43
Jet A1	6.90	8.20	9.15	9.96
Jet A1 + HVO (DCN = 51)	6.89	8.09	9.18	10.03
Jet A1 + SPK-FT (DCN = 51)	6.78	8.13	9.10	9.88
SPK-FT	6.56	8.00	8.98	9.90

Test conditions: *do*: 130 μm , *T*: 303 K, *P_{back}*: 5 MPa, *ET*: 2 ms, *n*: 6.

Table A8. Example of total injected energy (J) at different injection pressures tested.

Fuel	<i>LHV</i> ($\frac{\text{MJ}}{\text{kg}}$)	<i>Prail:50 MPa</i>	<i>Prail:70 MPa</i>	<i>Prail:90 MPa</i>	<i>Prail:110 MPa</i>
Diesel	42.66	293.46	355.59	402.54	445.11
Jet A1	43.08	298.25	354.13	395.17	430.25
Jet A1 + HVO (DCN = 51)	43.38	298.52	350.90	398.05	434.83
Jet A1 + SPK-FT (DCN = 51)	43.42	294.35	353.06	394.96	428.80
SPK-FT	44.32	291.85	355.89	399.30	440.21

Test conditions: *do*: 130 μm , *T*: 303 K, *P_{back}*: 5 MPa, *ET*: 2 ms, *n*: 6.

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