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Impact of cold conditions on diesel injection processes of biodiesel blends

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ABSTRACT

In this article, we report experimental results on the impact of cold conditions on diesel and biodiesel blends injection processes. We focus on cold conditions in view of the new Euro VI standards concerning problems related to cold-start. A Bosch CRI 3.1 piezoelectric injector was used on a typical diesel engine. Five fuel types were tested: diesel, winter diesel, diesel–biodiesel blends (B50), a winter diesel-biodiesel blend (B50(W)) and pure biodiesel (B100). Injection pressures of 30–60 MPa were tested (during start-up of the engine) in order to study the injection flow characteristics at room temperature and in cold conditions. Under cold conditions, the discharge coefficients for all fuels were lower than at room temperature. When the fraction of biodiesel in the blend increased, the discharge coefficients decreased slightly. Spray penetration increased and spray angle strongly decreased in cold conditions. This behavior was particularly clear for the B100 fuel. Winter diesel despite a higher viscosity than diesel showed most interesting performance in terms of discharge coefficient both at low temperature than at room temperature. These benefits disappear with the blend with biodiesel. New correlation coefficients for estimating the discharge coefficient and the spray angle are presented for cold conditions.

1. Introduction

Nowadays biodiesel, in particular blends with 2–20% diesel fuel, is increasingly used to partially replace fossil fuel [1,2]. The reason for the popularity of biodiesel is that biofuel is an agricultural product and a sustainable alternative energy source, it is environmentally friendly with reduced GHG emissions according to life cycle assessments (LCA), and has a higher cetane number and lower sulfur and aromatic contents [3]. The main disadvantages of biodiesel are its higher viscosity, lower energy content, higher cloud and pour points, higher nitrogen oxide (NOx) emissions, lower power and high price [1]. It is important to determine the viscosity evolution of biodiesel blends in cold conditions, especially during engine start-up. Pollutant emissions from biodiesel fuelled vehicles have received particular attention as in 2015 they have to respect Euro VI regulations. The new standards include cold-start problems, i.e. evaluation of post-treatment strategies and exhaust gas recirculation (EGR) at low temperature. The quality of the cold start at −7 °C is an increasingly stringent constraint [4]. While diesel-biodiesel blends under 5% do not impact cold flow properties [5], the emissions due to the use of biodiesel may not meet the new European standards. It is therefore necessary to consider the use of biodiesel in cold conditions in vehicle engines [5–7], to determine the physical properties of injection and flow characteristics inside the injector, the spray tip penetration, spray angle and fuel atomization in order to improve the characteristics of biodiesel, the fuel injection method and thus achieve the highest engine efficiency and low emissions.

Under standard temperature conditions, many studies [6–11] have highlighted the influence of fuel properties on the performance of the injector. When the viscosity increases, the flow rate in the nozzle decreases slightly, favoring the appearance of larger drops in the spray atomization. However, a decrease in the discharge coefficient was not observed with biodiesel blends, only with pure biodiesel (B100) [12,13]. Research shows that it is not

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easy to find a relation between the fuel mass flow rate and temperature. It depends on the type of injector and type of fuel [14,15]. Under cold conditions, the discharge coefficient (Cd) decreases strongly with an increase in viscosity [4,14]. Kegl [16] studied a specific configuration (a single injection assembly of inline fuel injection) and the impact of temperature on biodiesel. He showed that when the temperature decreased the injection duration, injection timing, mean injection rate and injection pressure increased. Tinprabath et al. [4] studied the influence of biodiesel and diesel fuel blends on the injection rate under cold conditions, and demonstrated that the fuel viscosity changes the injection duration and hence for the same pulse duration it also changes the total mass injected. Moreover at low temperature the fuel begins to gel and then to crystallize. A first wax formation is observed at the cloud point and then the crystallization leads to clogging of filters and the malfunction of the pump (CFPP). Specific fuels were made to be distributed during most winters (Winter or Artic Diesel). Additives limit the agglomeration of crystals and allow obtaining a cloud point or CFFP much lower. Beyond this fact, what impact this type of fuel blended with biofuel on performance of the injector? It has been shown in a previous study [4] that the Winter Diesel despite a higher viscosity than Diesel showed most interesting performance in terms of discharge coefficient both at low temperature than at room temperature.

Several publications show that when the percentage of biodiesel is increased, spray tip penetration also increases and the spray angle decreases [8,11,13,17,18]. Increasing the viscosity increases the spray Sauter Mean Diameter (SMD) and reduces the atomization capacity [14]. According to the literature, biodiesel fuel produced from vegetable or animal oils can be used with diesel injectors. Payri et al. [19] observed the effect of fuel properties on diesel spray development in extreme cold conditions (−18 °C), and found that the penetration length was clearly increased. Desantes et al. [11] studied three varieties of biodiesel produced from rapeseed: pure biodiesel (B100), and two biodiesel blends (5% and 30%). The results showed that only pure biodiesel had a negative impact on the spray behavior.

The main objective of this work is to study and to investigate at nearly -7 °C following Euro VI regulations. In the present study, the chosen fuels were diesel fuel, winter diesel fuel, biodiesel (rapeseed biodiesel), diesel fuel 50% rapeseed biodiesel, and winter diesel fuel blended with 50% rapeseed biodiesel. These mixtures are interesting because they have similar viscosities for different additives B50/B50W. The fuel properties were measured at the operating temperature and at 8 °C, 0 °C, −5 °C, and −8°. The novelty of the investigation is the study of fuel injection processes and the macroscopic behavior of the spray: opening delay, injection duration, discharge coefficient, penetration length of penetration and spray angle. The previously established correlations will be tested [6], the effect of winter additives will be discussed in the biodiesel blends.

2. Experimental apparatus

2.1. Experimental setup

Two experimental test rigs were used: an injection rate test rig and a visualization test rig. For the two experiments a prototype Bosch CRI 3.1 piezoelectric micro-sac injector with three convergent (an *AR* of 38% following [20]) orifices 100 μm in diameter with a pump and a pressure fuel tank were used [6,12,13]. All the injection and visualization equipment was installed in a climatic chamber to control the temperature in the experiment. Injection pressures were set at 30–60 MPa so as to be close to start-up conditions. The fuel injection rate was analyzed with an IAV® Injection Rate system (model K-025-50) [21]. This system detects and processes the dynamic pressure generated by injection into tube loops filled with fuel. The duct is pressurized by an adjusted nitrogen supply until 2.5 MPa as shown in Fig. 1. The injection rate is computed by Eq. (1), where $\dot{m}$ is the mass flow rate, S_{tube} the cross sectional area of the tube, a the fuel sound velocity and $p(t)$ the dynamic pressure.

$$\dot{m} = \frac{S_{tube}}{a} p(t) \tag{1}$$

Macroscopic visualization was accomplished using a constant-volume vessel with optical access and a constant circulation of air near the window as shown in Fig. 2. To obtain the desired density conditions inside the vessel, the pressure was adjusted; the system is designed for a maximum pressure of 3 MPa. The fuel injector is located at the top of the vessel. An 8-bit (256 gray levels) high speed camera (Photron®PowerViewTMHS-2000) recording at 15,000 frames per second was used to capture the three sprays by Mie scattering. Illumination was provided by a continuous 150 W halogen lamp. The camera and lamp are outside the climatic chamber, only a fiber light is inside. The image processing is based on the work by Tinprabath et al. [6] and Dernotte et al. [13]. For each operating condition, 50 injections at a frequency of 1 Hz were recorded to ensure convergence of the results.

2.2. Injection analysis

The injection rate was analyzed following the method of Tinprabath et al. [6], Dernotte et al. [12], and Payri et al. [14,21]. The mean mass flow rate, $\dot{m}_{measured}$ from the quasi-steady state period 1000–2000 μs after the start of activation (SOA) (Fig. 3) was used to calculate the discharge coefficient Cd, by Eq. (2). This period avoids the transient phenomena related to the opening and closing phases of the injector [6,12]. The theoretical mass flow rate, $\dot{m}_{th}$ (Eq. (3)) determined from the continuity equation (Eq. (4)) depends on the geometrical cross-section and the inlet velocity, V_{mean} calculated with Bernoulli's equation (Eq. (5)):

$$Cd = \frac{\dot{m}_{measured}}{\dot{m}_{th}} \tag{2}$$

$$\dot{m}_{th} = n_{orifice} \cdot S_c \sqrt{2\Delta P \cdot \rho_f} \tag{3}$$

$$\dot{m}_{th} = n_{orifice} \cdot \rho_f \cdot S_c V_{th} \tag{4}$$

$$V_{th} = \sqrt{\frac{2\Delta P}{\rho_f}} \tag{5}$$

$$Re = \frac{V_{mean} \cdot D_o}{\nu} \tag{6}$$

$$V_{mean} = \frac{\dot{m}_{measured}}{n_{orifice} \cdot S_c \cdot \rho_f} \tag{7}$$

where $n_{orifice}$ is the number of orifices on the geometric cross-sectional area of the orifice outlet, ΔP the pressure differential (ΔP = injection pressure, Pi − back pressure, Pb), ρ_f the fuel density at the experimental temperature, and V_{th} the theoretical velocity at the fuel outlet section. Re the Reynolds number is calculated by Eq. (6), where V_{mean} is the fuel mean velocity at the orifice exit, D_o is the geometric outlet diameter and ν is the kinematic viscosity of the fuel at the experimental temperature at atmospheric pressure.