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A novel experimental test rig for simulating of the fuel injection system components behavior under cold conditions

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ABSTRACT

In recent years diesel direct injection engines have been received more attention due to their high fuel efficiency and torque characteristics compared with gasoline engines. However, the cold start difficulties and cold diesel fuel behavior are still important issues which need improvement. In this study, a novel experimental facility has been developed using Stirling engine for fuel cooling and estimating the gel point and CFPP of diesel fuel and evaluating of the very cold diesel fuel behavior inside high-pressure common rail diesel fuel injection system. The results showed that the diesel fuel that is produced inside Iran has the capability to flow inside fuel injection system at temperature of -25^{0}C without using anti-freeze. The results also provided a good understanding of cold diesel fuel behavior and the test rig can be used for evaluating the fuel injection system components under ultra-cold conditions.

1) Introduction

To improving performance and reducing the emissions of the diesel engine especially in the passenger cars, it is needed to understand the behavior of the diesel fuel injection system components at the cold temperature conditions. Where the low-temperature affect the engine starting and its operation [1, 2]. Those can be induced by following powertrain phenomenon [3]:

- Fuel Filter clogging
- Injector clogging
- Fuel pump stall
- Overpressure in the electric fuel feeding pump

One of the main challenges of modern diesel engines is their fuel system behavior at cold conditions. Starting and working of diesel engines in cold weather especially with temperatures below zero centigrade temperatures is very hard. The difficulty of the cold start is because of poor air–fuel mixing and incomplete combustion [4, 5].

All diesel fuels include wax molecules. These are natural components of the crude oil that diesel is produced from. Wax is truly an essential diesel component as it has a high Cetane value, which gives good combustion quality [6]. The low compression temperature reduce the fuel vaporization process, leading to incomplete combustion [7] where the density and viscosity of diesel fuel increased during low ambient temperature [8]. The unburned hydrocarbon (HC), PM and carbon monoxide (CO) would be increased due to the incomplete combustion [9, 10, 11].

A few of previous works (almost none) have explained the diesel fuel system behavior at low fuel temperatures. Winter conditions, especially in Iceland or cold countries, where the diesel gets cold enough, the wax will start to crystallize (solidify). If enough wax crystals form, they will block the fuel filters, fuel strainers and fuel lines in diesel system. It is important to note that fuel quality is only one of the factors that may contribute to blockages in colder weather. Even if winter grade diesel is used, fuel systems may become blocked as a result of poor design. So, there are many factors like the effect of low temperature on low and high pressure pump also the Cold Filter Plugging Point (CFPP) issue should be understood to improve the cold start ability.

The idea of developing a special test rig by using Stirling engine has been introduced in this study to test the diesel fuel and other parts of HPCRIS[1] in case of very low fuel temperatures with very good controllability and low cost compared with different expensive test rigs provided by using climatic rooms and special refrigerators.

The aim of this paper is to test three different Iranian diesel fuels (From different suppliers) and two diesel fuel filters by using the cold rig test engine reduction system and investigate the effects of fuel temperature on the high-pressure diesel fuel injection system. By means of this test rig, a basic understanding of the fuel behavior in cold conditions can be achieved systematically at room temperature and its influence on the fuel filter

2) Experimental setup

A free piston EG-1000 engine/generator illustrated in Figure 1 has been used in this study to reduce the fuel temperature. The refrigerator section in the head of Stirling engine has been used as a cold source to reduce diesel fuel temperature. EG-1000 engine module was developed to produce 1kW of electric power in a laboratory from solar energy [12, 13].

Figure 1: EG-1000 Stirling Engine

Basic Stirling engine had a cylindrical head with 100mm height and 100mm diameter. The cold temperature from the head of Stirling was obtained by reversing the work cycle through connecting to 220 volts, 50Hz power source also, a water cooling system has been used to remove the heat produced from hot side of the engine by using radiator and water pump.

A 6mm diameter and 6m length copper tube coiled around the cold head of Stirling engine to make a heat exchanging between Stirling head and the tube. A special paste was used to increase the cooling efficiency of the system through increase the contact surface of the cold area (copper tube and Stirling engine head) as shown in Figure 2.

Figure 3 shows schematic representation of diesel fuel cooling system. Three additional temperature sensors (k type) was used in this test rig to monitor the temperature at different places of fuel lines and Stirling engine.

The system was used to check diesel fuel behavior at cold condition, where freezing point for the different types of fuel can be calculated. In the other hand, the experimental setup has the ability to examine several

[1] High Pressure Common Rail Injection System

types of diesel fuel filters and other components of fuel injection system like fuel lines, low pressure and high pressure fuel pump and fuel rail. The CFPP temperature of each part can be calculated using the system.

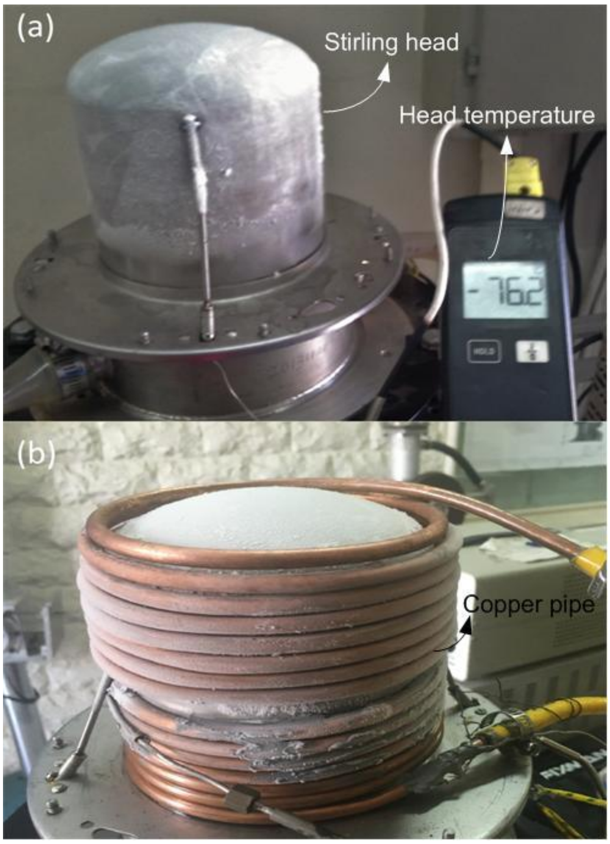

Figure 2: (a) freezing head of Stirling engine and (b) the copper pipe around Stirling head

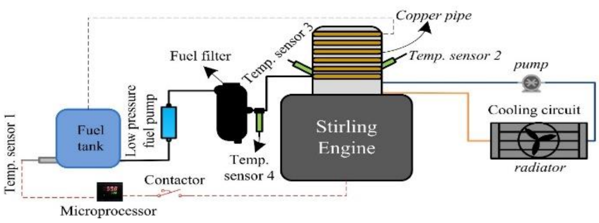

Figure 2: Schematics of cold diesel fuel system components (low pressure circuit)

3) **Experimental conditions**

To characterize the fuel behavior at cold temperature and CFPP for diesel filter as accurate as possible, three types of Iranian diesel fuels were utilized. Nominal diesel fuel specifications are listed in Table 1. Diesel fuel samples gathered from different Iranian refineries. For the tests the fuel samples called D1, D2, and D3. It should be noted that the specification of 3 fuel samples was according to EN 590 standard (Table 1) except sulfur content and CFPP point that was different. Anti-gel additive was added to D1 diesel fuel type to improve fuel work at very cold temperature. Also, two types of diesel fuel filters (F1 and F2) were tested that was related to two commercial filter suppliers each one had a 12V heater for cold operation. It should be noted that heater was switched off during this test.

Table 1: Table 1 Diesel fuel properties

Property	Unit	Value
Cetane number	-	51
Density at 15°C	kg/m^3	820-845
Viscosity at 40 °C	mm^2/s	2-4.5
Water content	mg/kg	200

4) Results

Stability of using diesel fuel temperature reduction system

In order to check the accuracy of the fuel reduction system which had been explained above, the stability of using Stirling engine for reducing the fuel temperature was tested as shown in Figure 4. For studying diesel fuel behavior and the effect of fuel temperature on diesel fuel injection system, it's important to have a system with a very low level of the temperature fluctuations at different set points during the test period.

As shown in Figure 4 the electrical circuit of the system had a good controllability on the Stirling engine operation thus, provided a good stability of the fuel temperature at the set point equal to -10^{0}C with using D1 diesel fuel type. The test took about 25 minutes to reach to the -10^{0}C and the system worked on the set point temperature for about 35 minutes without any problems with maximum fluctuation range ± 0.7^{0}C.

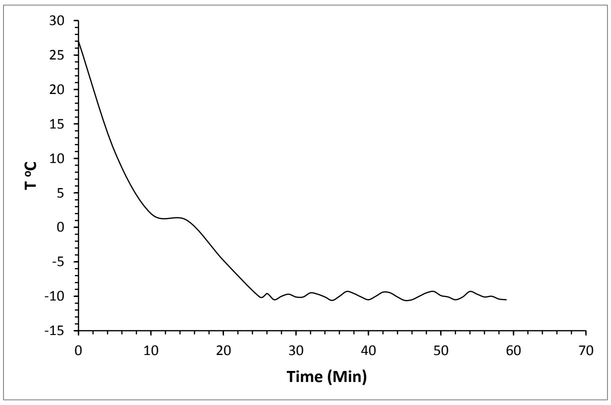

Figure 3: stability of the fuel temperature adjustment system at the set point of -10^{0}C by using D1 diesel fuel

Diesel fuel behavior at cold condition

As EFD engine is in the start of the production phase, the Iranian diesel fuel should be investigated in many aspects to prove that this fuel could be applicable for light duty diesel engine. Thus, in order to have a complete information about the CFPP point of these fuels and to have the best solution for diesel fuel to be suitable for working in winter and cold conditions, three different Iranian diesel fuels have been selected to investigate their behavior. The used diesel fuel was gathered from different Iranian refineries. D1and D2 fuels gathered from Shazand refinery and D3 from Tehran refinery where these fuels are the best Iranian diesel fuels in case of sulfur content (below 50 ppm) and CFPP.

As shown in Figure 5, D3 fuel has been checked with three different setpoint temperatures of -5, -20, -25 ^{0}C. It took about 17 minutes to reduce the fuel temperature from ambient temperature to -5 and -20 ^{0}C and 23 minutes to reach to -25 ^{0}C. The fuel cold working behavior at different temperature set points is shown in Figure 5. From this figure, it can be observed that the system has good temperature stability and after 25 minutes the fluctuation range was ±0.5 ^{0}C. For this reason, the system can be used to study cold properties of different fuel types. It should be noted here that as shown before in Figure 3, experiments of this section, have been implemented in the low pressure section of fuel injection system i.e. the fuel did not enter the high-pressure circuit.

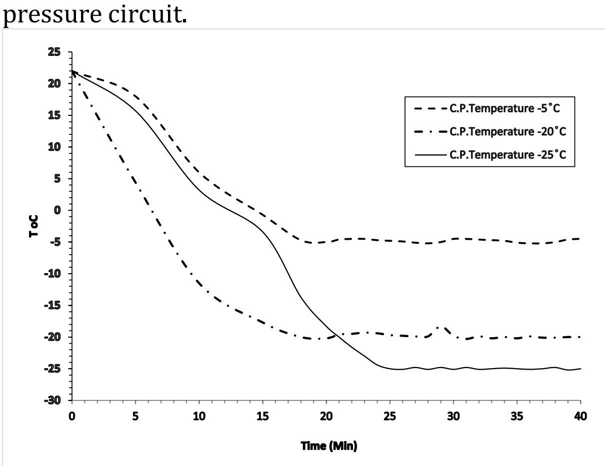

Figure 5: D3 Diesel fuel behavior at different setpoint temperatures

Figure 6 shows the results of the gelling point measurement for three fuel types D1, D2, and D3. The measurement factor of the test was the flow of the diesel fuel through the copper tube around Stirling head. Most diesel fuels include a significant proportion of components, which include waxes. At low temperature, the precipitation of paraffin crystals (wax) can cause clogging of the fuel lines, filter and an interruption in the fuel supply [14]. Thus, wax contains fuel can be clogging the fuel flow inside the copper pipe of the system.

The test was started with set point equal to -5^{0}C for all types of fuel and gradually reduced (-5^{0}C for each step) to reach the temperature that the fuel flow will be stopped, which means that the fuel reaches the gelling point temperature. Figure 6 indicates that fuel cooling stopped after time elapsing. D3 type reached to -25^{0}C for about 40 minutes without any problem. However, the fuel pump was stopped with set point temperature lower than -25^{0}C which means that the fuel cannot be flow through the pipe with a temperature lower than -25 ^{0}C.

Thus the cloud point of fuel or gelling point can be estimated. Also, D1 fuel type temperature reached to -17.3^{0}C and the fuel flow inside copper pipe had been stopped after 30 minutes of the test where the fuel can pass the test with a set point of -15^{0}C and failed with -20^{0}C. Also, D2 fuel cannot be passed through the pipe at the temperature lower than -9.8 ^{0}C. The values that are extracted from this novel experimental setup for fuel cold point or gel point are similar to the values reported from the standard test of the fuel.

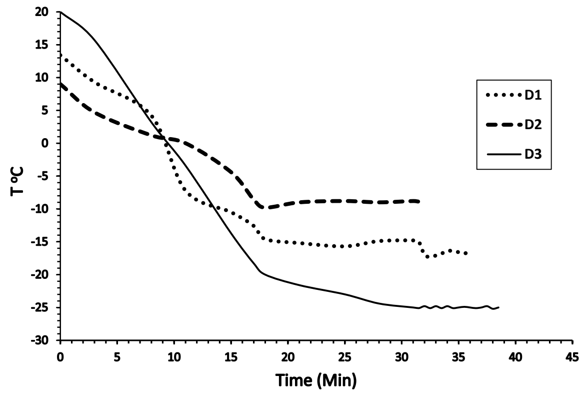

Figure 4: cold temperature test for three different diesel fuels

Test of diesel fuel filters at cold temperature

Three problems occur when the fuel temperature decreases to minus degrees. Firstly, the water content in the diesel fuel will freeze and plug the fuel line and filter. Secondly, wax in the fuel solidifies and restrict fuel lines, filters and other fuel system components. The third problem with diesel fuel at cold temperature occurs as the fuel is cooled below the cloud point and more wax precipitates. Where the fuel becomes so thick it will no longer flow through the fuel lines. This temperature is known as the poor point [15].

For testing filters, D1 Diesel fuel with Antigel (ice proof for diesel contains from kerosene and naphthalene) was used. The test was performed by using two types of diesel fuel filters, F1 inline metallic fuel filter with filter heating showed in Figure 7 (a) and F2 inline plastic filter with filter heating showed in Figure 7 (b).

Figure 8 shows the reduction of fuel temperature during the test of diesel fuel filter (F1). In this test, the set point temperature of the system was equal to -200C. After about 38 minutes, fuel temperature reached to -17^{0}C and the fuel at this temperature passed through the filter without crystals forming and this was the minimum temperature the fuel can circulate inside the filter. For the fuel temperatures lower than -17⁰C, the filter has been rejected because the failure in the filter drains O-ring.

The difference between fuel tank temperature (measured by sensor 1 (Figure 3)) and outlet fuel temperature of the filter (measured by sensor 4 (Figure 3)) is presented in Figure 9 by using F2 diesel fuel filter. Test shows about 4⁰C different between the temperature of in fuel tank and the outlet of filter caused by the pressure drop in the fuel filter outlet. This measurement provided a good understanding of the fuel temperature behavior after fuel filter in order to check filter operation at cold fuel temperature and control the fuel temperature inside the high-pressure fuel system. `

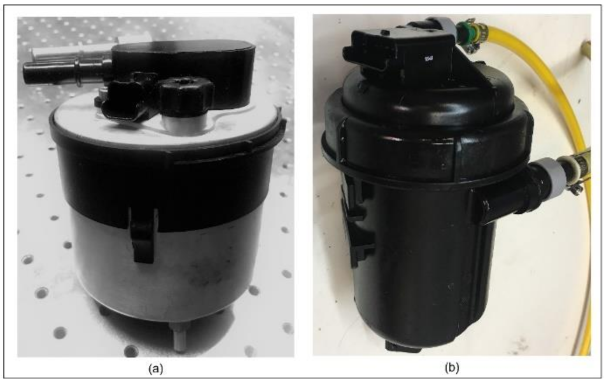

Figure 5 : Tested diesel fuel filters (a) F1 (b) F2

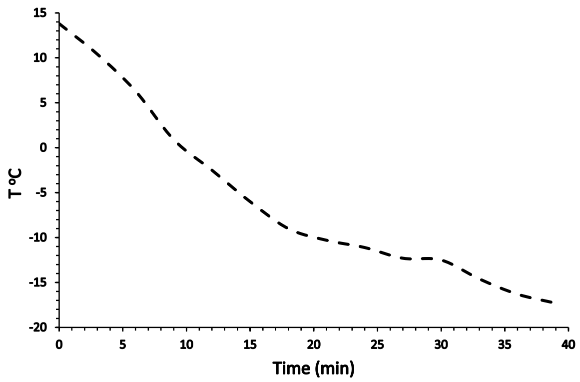

Figure 6: F1 diesel fuel filter test

F2 filter worked with temperature -7⁰C without using filter heater as shown in Figure 9 however, for the lower temperatures filter heater should be used to prevent filter plugging. Figure 10 shows the operation behavior of low pressure fuel pump with F2 filter. The standard methods were mainly used for determination of the Cloud point and CFPP of the filter presented in [16, 17] but, by measuring the current flow through the fuel pump circuit and use it as a factor can be determined the CFPP of the filter with D1 diesel type. Figure 10 shows a sharp rising in current at fuel temperature up to 8⁰C where the fuel pump was stopped with 10 Amp. The phenomena show that the D1 fuel at temperature up to -80C cannot pass through the filter.

The filter heater is one of the solutions to prevent solidification of the fuel inside the filter. To show the effect of the filter heater on the fuel behavior, F2 filter has been used for this purpose.

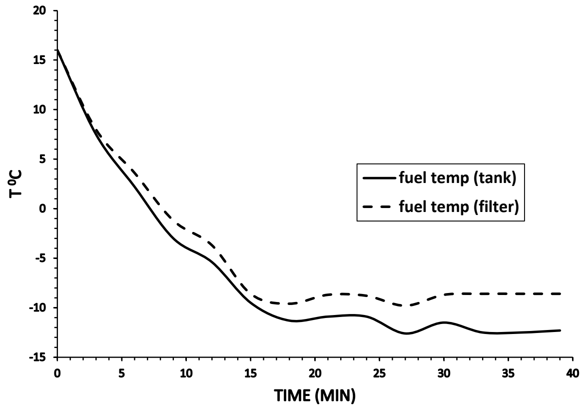

Figure 7: the temperature difference between the fuel tank and filter outlet

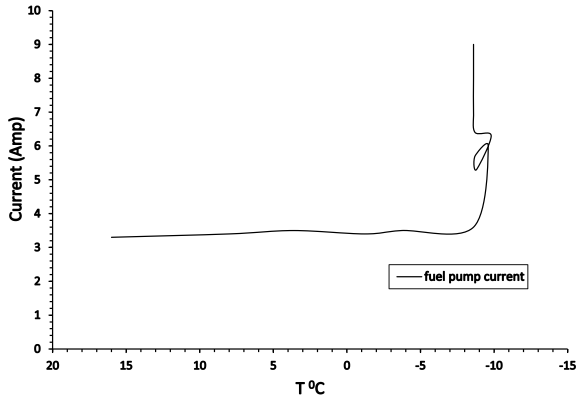

Figure 8: fuel pump current at different fuel temperatures with F2 filter

The test results of the F2 fuel filter with heater have been illustrated in Figure 11. The minimum temperature which the fuel can pass through F2 filter based on the above tests was -8⁰C. Thus, for this test, the heater was seated to work with temperature range -7± 3°C by using voltage power supply. As shown in Figure 11 the heater turned on at temperature more than -10⁰C and stopped with temperature lower than -3⁰C.

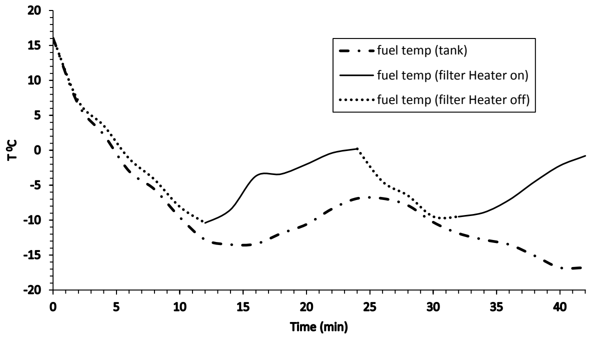

Figure 9: F2 diesel fuel filter test with and without using a heater

The test showed that the temperature inside the fuel tank reached to -17⁰C and the filter outlet temperature fluctuated between 0.2 and -10.4 ⁰C with using the heater. Thus the test of the F2 filter shows that the fuel filter with using heater can work at low fuel temperatures -17⁰C for the D1 type of fuel. Also, shows that the CFPP of the filter reduced from -8⁰C without using heater to -17⁰C by using the filter heater.

However, using the fuel filter heater is not enough to prevent filter clogging because fuel strainer inside the fuel tank may be blocked during the very low fuel temperatures so it is necessary to use special fuel for winter condition by using anti-gel fuel "cold flow improver" known as winterization fuel.

Conclusions

A special experimental setup has been used to study the influence of cold temperatures on the diesel fuel and diesel fuel filter. Where several types of Iranian diesel fuel and fuel filters have been used to provide an understanding of the cold diesel fuel flow inside of the injection system and clogged point temperature of fuel filter by using the Iranian fuel.

The results show that Stirling engine has good ability to reduce fuel temperature to very low degrees and the sophisticated proposed experimental test rig can be used for low temperature fuel effects investigation. Furthermore, the D1 diesel fuel type did not solidify inside the system with the minimum temperature equal to -17⁰C without using anti-gel and D3 fuel type did not frozen inside the system with -25⁰C fuel temperature also, D2 fuel solidify with the temperature lower than -7⁰C. In the other hand, F2 fuel filter plugged at a temperature lower than -5⁰C (where the heater should be used) with D1 diesel fuel type.

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مجموعه آزمایشی جدید برای شبیه سازی رفتار قطعات سامانه سوخت رسانی در شرایط دمایی بسیار سرد

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چکیده

موتورهای دیزل به دلیل بازده بزرگ و گشتاور زیاد در سال های اخیر به نسبت موتورهای بنزینی بیشتر مورد توجه قرار گرفته اند. اما مشکلات مربوط به راه اندازی سرد در رفتار سوخت دیزل در دماهای بسیار کم مسائلی هستند که نیاز به بهبود دارند. در این تحقیق یک مجموعه آزمایشی جدید برای سرد کردن سوخت، تعیین دمای ژل شدن و اندازه گیری مشخصه CFPP سوخت و سنجش عملکرد سامانه پرفشار تزریق سوخت در دماهای پایین با استفاده از موتور استرلینگ توسعه داده شد. نتایج نشان داد، سوخت دیزل تولید داخل قابل این را دارد که در سامانه سوخت رسانی موتور دیزل تا دمای $-25^{o}C$ بدون استفاده از افزودنی جریان پیدا کند. نتایج همچنین درک درستی از عملکرد سوخت دیزل در دماهای کم ارائه داد و سامانه ساخته شده می تواند برای ارزیابی قطعات سامانه سوخت رسانی موتور دیزل در دمای کم مورد استفاده قرار بگیرد.

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