TEMPERATURE INFLUENCE ON THE FUEL DROPLET SIZE

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ABSTRACT

The Bosch Flex Start System is a cold start concept aimed to ensure the start of internal combustion engines in the first attempt, mainly when they are filled with ethanol and face low temperature climates (below 15ºC). In that system, the fuel is preheated before being injected into the engine cylinders, through a fuel rail containing individual heaters. The heated fuel injection allows its entry into the engine combustion chambers in a more pulverized way, which, besides of ensuring the engine start in the first attempt, improves the ethanol burning, reduces the gases emission level and provides good steering conditions.

It is known that, the smaller injected fuel droplet size (bigger pulverization) the better will be its combustion. Thus, this article will aim to present a study regarding the injected fuel temperature influence on the droplet size. According to data acquired from practical tests, it will be possible to evaluate the temperature vs droplet size curve and take decisions on how to optimize even more this system, mainly regarding energy efficiency of vehicle as a whole.

Resumo

O sistema Flex Start Bosch é um conceito de partida à frio que visa garantir a partida de motores de combustão interna na primeira tentativa, principalmente quando estes estão abastecidos com etanol e enfrentam climas de baixa temperatura (abaixo de 15ºC). Neste sistema, o combustível é pré-aquecido antes de ser injetado nos cilindros do motor, através de uma galeria equipada com aquecedores individualizados. A injeção do combustível aquecido permite que ele entre nas câmaras de combustão do motor de forma mais pulverizada, fato que, além de assegurar a partida na primeira tentativa, melhora a queima do etanol, reduz o nível de emissões e permite boas condições de dirigibilidade.

É sabido que, quanto menor for o tamanho da gota do combustível injetado (maior pulverização), melhor será sua combustão. Assim, este artigo terá como objetivo apresentar um estudo sobre a influência da temperatura do combustível injetado sobre o tamanho da gota. Com base em dados obtidos através de provas práticas, será possível avaliar a curva de temperatura x tamanho de gota e tomar decisões para otimizar ainda mais este sistema, principalmente no que tange à eficiência energética do veículo como um todo.

INTRODUCTION

During the last years, Brazilian vehicle Market is seeing an increase of fuel heating devices used to enable engine start at cold temperatures, when vehicle is powered with ethanol fuel. Such systems heat fuel until it reaches the ideal temperature for good combustion inside engine cylinders. These heating systems were developed for flex fuel PFI engines (port fuel injection), working with fuel pressures from 3 to 5 bars. Low pressure engines are still and will remain the predominant concept for passengers cars used in Brazil in the next years. For this reason, studies related to fuel heating will help to improve engine efficiency, especially due to the new upcoming national engine emission legislation.

The study presented here, investigates the influence of temperature on the injected spray when one of these heating devices heats fuel. Flash boiling point is also part of this study, when such heated fuel is then injected into a low pressure environment (for example, combustion chamber), the fuel temperature may exceed the boiling point that triggers the flash boiling [1,2]. The size of the injected droplet plays an important role to improve fuel combustion, especially at cold starts, and, consequently, reduce emission levels. Therefore, understating the behavior of heated sprays can optimize air-fuel mixture and enhance driveability.

The SMD (Sauter mean diameter) was measured for two fuel types (n-heptane and E100 – Brazilian ethanol) with different fuel pressures, and used as comparison for analysis.

1. THEORY

1.1. Fuel Spray Atomization

1.1.1. Droplet size

With the tighter emissions laws that are coming to Europe, United States and also the underdeveloped countries, the combustion efficiency is more and more analyzed to improve the fuel consumption. This better efficiency is deeply connected with air fuel mixture and consequently the fuel atomization, which is the droplet size of the fuel, when it is injected in the combustion chamber. As better as the atomization, lower droplet size, better is the combustion, once it is easier to burn a droplet as is small it is, once the contact area exposed to the heating is higher, improving the heating transfer.

1.1.2. Types of droplet size calculation

If the droplet was a perfect sphere, it would be easy to determine a dimension to define the droplet size. However, it is not a perfect sphere, so, the challenge was to define a magnitude to provide a value for further comparison, for example, such as combustion efficiency relation with droplet size. Due to this necessary for a value that can be used to evaluate the atomization quality, and it must be given through one number, the sphere was defined to be the magnitude to specify the droplet size.

Nevertheless, as the droplet is not a perfect sphere, it is a calculation. The size provided by this calculation will be given through a specific technique, so, each calculation method will provide a different result, being important to always compare the sizes based on the same technique [3]. The differences in the numbers does not mean that one technique is wrong and the other is right, but they show that each technique considered a different parameter for the calculation.

There are some possible ways to calculate the droplet size. The first one is D(1,0), which considers the mean value from the particles, so, it is summed the size divided by the quantity of particles, considering only one unit provided.

The second one is the D(2,0), which considers the surface of the particles, once higher is the surface area, higher is the catalyst effect. So, in this method, the size is considered the square sum divided by the particles quantity and to get back to the diameter it must take the square root, as showed below.

$$D(2,0) = \sqrt{\frac{\sum d^2}{n}}$$

The third one, D(3,0) considers the weight, hence it is the sum of the cube the diameters divided by the quantity of particles.

$$D(3,0) = \sqrt[3]{\sum \frac{d^3}{n}}$$

These three first methods are not applicable when the numbers of particles are big, once it become the counting difficult regarding accuracy. So, the most important methods to calculate the droplet size are: D(4,3) and D(3,2), which do not have dependency with particle numbers.

D(4,3) is volume or mass moment mean and D[3,2] is surface area moment mean.

$$D(4,3) = \frac{\sum d^4}{\sum d^3}$$

$$D(3,2) = \frac{\sum d^3}{\sum d^2}$$

In the automotive business the standard method for droplet size measurement is the D(3,2) SMD.

1.1.3 SMD definition at Bosch

There are three different definition at Bosch for Overall SMD (or mean SMD) calculation:

1. Weighted SMD: It considers the weighted SMD value by the volume measured each delay time of measurement.

   a. $SMD = \frac{SMD_1.V_1 + SMD_2.V_2 + \cdots + SMD_n.V_n}{V_1 + V_2 + \cdots + V_n}$

2. Average SMD: It considers the average from Plateau Region, normally between 6,0 to 8,8 ms of delay time of measurement .
3. SMD OBmax: It considers the SMD from the obscuration peak.
   The obscuration definition is how much the laser is absorbed by the droplets.

Weighted SMD is the method applied in this work.

1.2. Fuel Heating

In Brazilian market, fuel heating systems are being used for engine cold start assistance since 2009, replacing the gasoline sub-tank, concept used since the development and creation of ethanol powered vehicles. The heating system most commonly used in the market, consists of a heater, placed inside the fuel rail, near to the entrance of each fuel injector [4, 5, 6]. Only a specific portion of the fuel storage inside the fuel rail is heated, to efficiently transfer energy and reduce heat losses. A specific control unit is used to drive power to the heaters according to calibration inside the ECU (engine control unit). Before starting the engine, the control unit checks the environmental temperature and checks the last fuel used, to then start heating the fuel until it reaches the target temperature for enabling engine start. Normally, fuel heating is needed for ambient temperatures below 20°C, and fuel must be heated above 80°C to successfully start engine, when powered with 100% ethanol fuel. The target temperature may vary from engine to engine, and of course, environmental temperature. The system keeps heating the fuel until engine is hot enough to run without heat assistance.

Systems can heat fuel near its vaporization temperature, achieving temperatures above 100°C, and thus changing the behavior of the injected spray into the combustion engine. Therefore, the temperature influence on the droplet size will be the focus study described on this paper.

Figure 1. Example of heated fuel rails

2. METHODOLOGY

To quantify and evaluate the fuel temperature influence on the droplet size, a measurements bench was used as shown in the figure 2.

Figure 2. Droplet Size bench test measurement (Malvern)

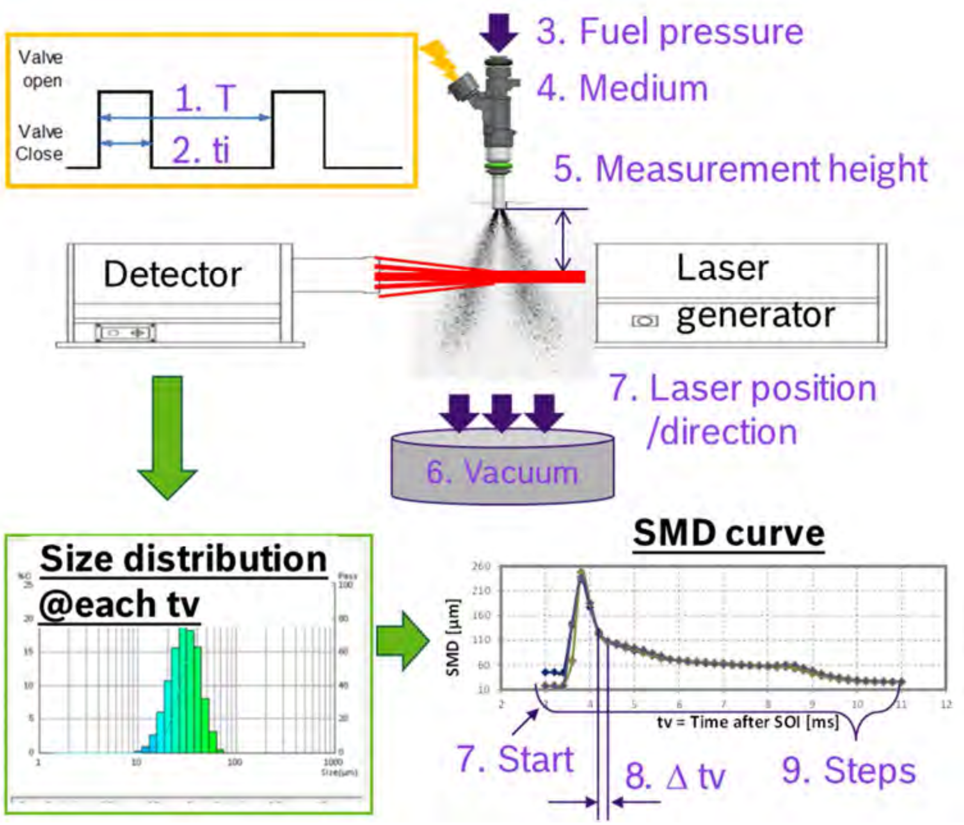

Figure 3. Test bench principle

The fuel injector tip is positioned in a distance from the laser equal to 50 mm (called of distance z: measurement height), the fuel injector is activated and the spray pass through the laser and the droplets diffracted the laser from the straight path, which depending on the diffraction determines the droplet size. The diffracted laser position and intensity are detected by sensor, and droplet size distribution is calculated.

The measurement standard is:

- Fuel injector operation with period (T) of 20 ms and an injection time (ti) of 6 ms.
- Than the droplet size measurement in the following delay times: 2,8 ms, 3,6 ms, 4,0 ms, 4,4 ms, 4,8 ms, 6,0 ms, 6,8 ms, 7,6 ms, 8,4 ms, 9,2 ms, 10,0 ms, 11,0 ms, 12,0 ms and 13,2 ms, totalizing 14 points. Those points follows to get SMD peak in the first points and its reduction in the end.

As results, the software can provide droplet size values, volume measured and obscuration at each delay time.

This bench does not test with heated fuel, however, for this study, a heating system containing a smaller fuel rail (one heating chamber) was implemented, where a heater and thermally insulated hoses were placed to drive the heated fuel.

The temperature was monitored by a type K thermocouple installed at the point closest to the injection valve inlet and controlled by the power supplied from the source to the heater.

The figure 4 shows the heating system assembly on the fuel inlet of the machine:

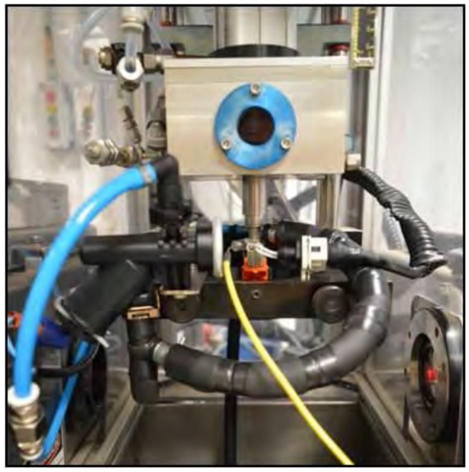

Figure 4. Fuel heat system

It is known that the factors that may influence on the fuel droplet size are: Fuel Temperature, Fuel Pressure, Flow Rate, Spray Angle (spray cone angle), Fluid Type and Fuel Injector Orifice Plate Design [7]. For this study, only the temperature variation, pressure and type of fluid were observed.

For this work, the injection valve used was EV6-P with a single cone angle (C-type spray) that have following characteristics:

- Static Flow (Qstat) = 114,80 g/mi , measured at 3 bar with n-heptane
- Dynamic Flow (qdyn) = 3,55 mg/pulse , measured at 3 bar with n-heptane and T of 10 ms and ti of 2,5 ms.
- Spray Cone angle (alpha) = 17,3 ° , measured at 3 bar with n-heptane

Figure 5. EV6 example.

The study was carried out in five different temperatures: 20, 40, 60, 80 and 100ºC, with two fuels type: E100 (ethanol) and n-heptane and in two pressures: 3 and 5 bar.

For 20ºC, the heating system was not used, since it is already the standard temperature of the bench (Room Temperature), however, for the other temperatures, an electric power source was used where the voltage level was gradually increased until the heater heated the fuel to desired temperature. To keep the fuel at temperature, it was necessary to monitor and adjust the voltage throughout the test.

The standard fuel for SMD evaluation is n-heptane, but for this study, ethanol was also used, where it was necessary to change the fuel and clean the tank after the exchange.

Another variable is the pressure, where it is adjusted through a variable regulator already existing in the machine.

3. RESULTS

As already mentioned the main goal of this work is to quantify the effect of fuel heating in the fuel injector spray atomization, therefore as also explained above temperature, pressure and fluid were the parameters chosen to study.

Fluid properties affect the droplet breaking, i.e., atomization, such as fluid density, surface tension and viscosity [8]. For example, by increasing the temperature, the fluid surface tension reduces and consequently the fluid can be broken more easily. Viscosity affects not only droplet breaking but also the spray pattern. Those are the reasons to have smaller droplet size when the fuel is heated, since fluid properties also change in the way to improve the droplet breaking process.

In table 1, surface tension variation with temperature is presented for two contents of ethanol fuel. Regarding n-heptane properties, since it is similar to gasoline, it is expected to have a higher surface tension than 100% ethanol by extrapolating the table values, where there is a clear the tendency of surface tension increase with ethanol content reduction.

Table 1. Surface Tension variation with temperature (extracted from [9]).

	Surface tension (mN m^{-1}) at temperature (°C)						
Ethanol %	20	25	30	35	40	45	50
90	23,23	22,72	22,32	21,94	21,53	21,13	20,71
100	22,31	21,82	21,41	21,04	20,62	20,22	19,82

First results were obtained by measuring SMD with n-heptane at 3 bar of fluid pressure. In figure 6 is possible to see a linear behavior between 20°C and 60°C, showing 8,1 µm reduction in the SMD. In the other hand, very high values of SMD were observed at 80°C and 100°C.

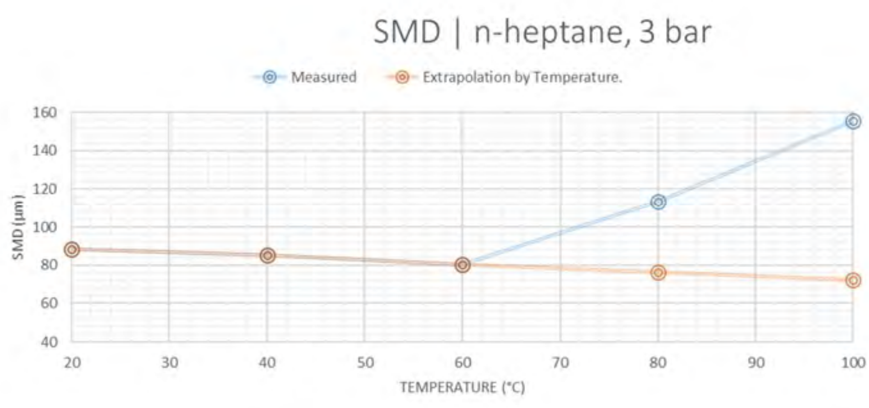

Figure 6. SMD results with n-heptane at 3bar.

At 80°C, the n-heptane already achieved the vapor pressure temperature, or, flash boiling point [1,2], meaning that instead of having liquid fuel droplets injection, a large amount of fuel vapor is injected by the fuel injector. Consequently, the laser cannot diffract accordingly in the vapor cloud, because its diffraction increases with vapor, thus masking the measurement of the droplet size.

To estimate the SMD at higher temperatures, an extrapolation was done by linear regression of SMD values for the first 3 measured points (SMD as a function of temperature): 20°C, 40°C and 60°C. This extrapolation shows that the SMD is closer to 70 µm (72,4 µm at 100°C), nevertheless is expected in the real results even lower values of SMD since it is already in the vapor phase.

In the second step, the pressure was increased to 5 bar. By this pressure, fuel injection speed increases, and fluid break up happens more easily. In figure 7, the results shows similar profile in comparison to 3 bar measurement, however with an offset of approximately 20 µm.

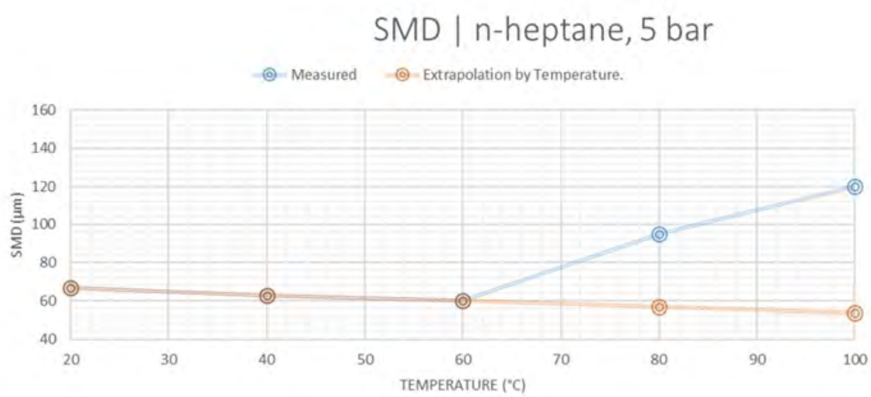

Figure 7. SMD results with n-heptane at 5bar.

Once again is noted a liner behavior of droplet size up to 60°C and a considerable gain due to fluid pressure increase: more than 24%.

SMD for ethanol (E100) were measured following the same steps: first at 3 bar than at 5 bar.

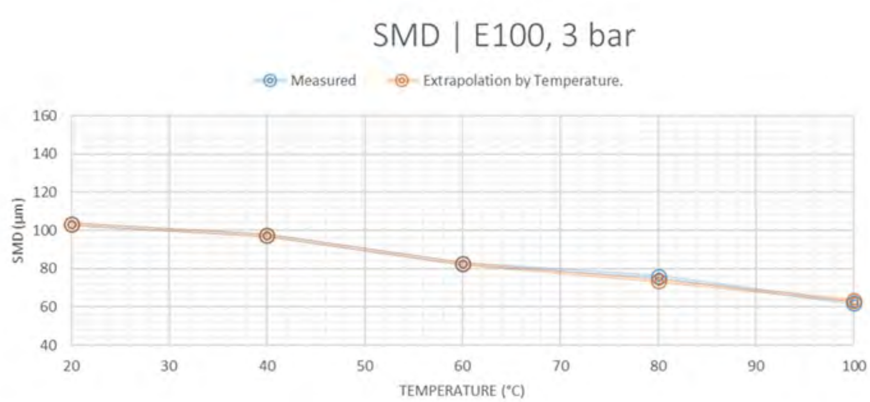

Figure 8. SMD results with ethanol at 3bar.

With ethanol there isn't a considerable vapor formation, and therefore, the correlation between extrapolation by temperature and measured results is also good at 80°C and 100°C. Again, the fluid pressure increase pushes the results down, with a offset in the SMD profile of approximately 20 µm. Basically the pressure effect is the same for n-heptane and ethanol. For ethanol is clear that SMD sensitivity is higher than with n-heptane: by 40°C temperature increase there is a SMD reduction of 20,5 µm.

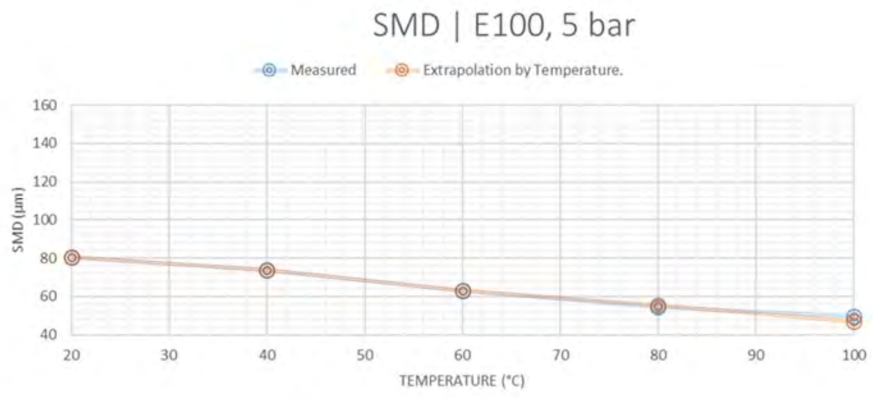

Figure 9. SMD results with ethanol at 5bar.

The SMD reduction in this case is higher than 33 µm when comparing the results at 100°C and at 20°C.

In table 2 there is a summary of all SMD weighted results, which is clearly showing the effects of heating in the atomization.

Table 2. SMD results summary [µm]

	Fluid	**Pressure** (bar)	**Temperature** (°C) 20	40	60	80	100
Measured	n-heptane	3	88,2	85,3	80,1	113,5	155,5
	n-heptane	5	66,7	62,6	60,2	95,1	120,2
	E100	3	103,0	97,3	82,4	75,7	62,1
	E100	5	80,4	73,8	63,2	54,3	49,8
Extrapolated by Temperature	n-heptane	3	88,2	85,3	80,1	76,5	72,4
	n-heptane	5	66,7	62,6	60,2	56,7	53,5
	E100	3	103,0	97,3	82,4	73,7	63,4
	E100	5	80,4	73,8	63,2	55,3	46,8

Figure 10 summarizes in a graphic all results for easier comparison. Since was not possible get real SMD of n-heptane at 80°C and 100°C, the comparison graphic considers the extrapolation values by temperature, as already explained in the previous results.

The variation ratio of SMD by temperature (derivative by temperature) is higher with ethanol than in n-heptane, i.e., SMD reduction by heating is higher in the ethanol spray than n-heptane.

@ 3 bar: Ethanol = -0,51 µm / °C

	n-heptane	= -0,20 µm / °C
@ 5 bar:	Ethanol	= -0,40 µm / °C
	n-heptane	= -0,16 µm / °C

Based on that, the benefits of atomization by heating should be higher in the ethanol usage than in the gasoline.

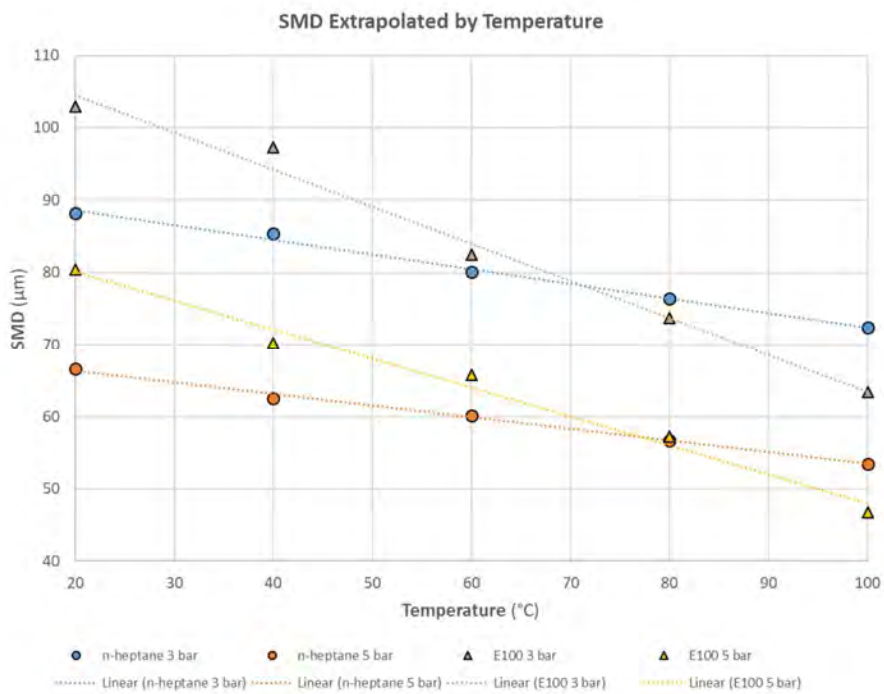

Figure 10. SMD results summary extrapolated by temperature.

According to Richer [10] the position of laser (z) will affect the results of SMD, since laser may sweep the injected fuel spray or not. They learned that at higher laser (z) position, such as 30 mm or 60 mm, the spray may not be evaluated, e.g., SMD is not measured accordingly. Therefore, the proposal as next step is to repeat this study measurement reducing laser (z) position from 50 mm to 10 mm, assuring that fuel spray is swept.

CONCLUSION

Among the several variables that influence on the fuel droplet size, this study evaluated the influence of fluid, temperature and pressure, where it is possible to observe some points:

- The influence of temperature increase on ethanol droplet size is more relevant than on N-heptane as shown on the results. So in the Brazilian market where there are many flex fuel cars, Bosch heating system works very well and brings many benefits for combustion efficiency as mentioned previously.

- Another variable is the pressure, the higher the pressure, the more vaporized the spray will be and consequently smaller the droplet size.

- Fuel heating is a clear process to improve the fuel atomization of the fuel injector spray. The heat increases fuel temperature, reducing the surface tension, density and viscosity of the fluid, improving the droplet breaking process during the injection. According to the measurements performed by fuel heating at 100°C, it is possible to reach a reduction level of SMD of 40%. The SMD reduction results in a higher increase of the contact surface area, which will improve the burning process, once the heating transfer is more efficient, this reduction of 40% in the SMD increases in 260% the contact surface area, showing that combustion can be highly improved with fuel heating mechanism. This enormous increase in the surface area is because it is the square of the SMD value, increasing much more than the SMD values.

The next steps will be to repeat the measurements, however, with the distance of 10mm between the orifice plate and the laser. This way, it will not be necessary to use extrapolation by the temperature for high temperatures in n-heptane and will allow getting more accurate SMD values.

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