Research Paper

Effect of Fuel Physical Properties on Spray Parameters of Residual Fuel Oil (RFO)

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ABSTRACT

This paper studied the effect of fuel physical properties on spray parameters of RFO. To achieve this, the fuel (RFO) was characterized to determine its physico-chemical properties, and an experimental set up was designed to visualize and capture the spray pattern of the fuel. After which images obtained were processed and analysed using Image J software to determine the spray length, spray cone angle, spray area, spray volume, and spray velocity values of the fuel. Results obtained showed that the viscosity of RFO decreases with increase in temperature. It was also seen that the high viscosity and surface tension of RFO accounts for the higher spray parameters values of 456 mm for spray length, 22.67° for spray cone angle, and 2.85 mm for SMD at a viscosity of 9.16 mPa.s. This condition, will lead to a higher spray volume causing the engine to run on a rich mixture after initial start-up conditions. This leads to challenges such as reduction in power and clogging of injector nozzle tip due to increase in carbon deposit.

Keywords: Viscosity, Density, Surface Tension, Spray length, Spray Area, Spray volume, Spray cone angle, Sauter mean diameter.

INTRODUCTION

Issues arising due to the instability of electric power in Nigeria have forced Small and Medium scale Enterprise (SME) to generate their own power in order to make their businesses thrive. This electric power is generated through the use of standalone power plants such as the gas, petrol and diesel powered generating set. The diesel powered electric generating set is more dominant because of its advantages of lower running and capital cost, ease of installation, simple plant layout, and ability to carry heavy electrical load. However, the high cost of diesel which translates to a high product cost makes it very difficult for these SMEs to maintain/attain influence in a competitive global market. To mitigate this challenge, the resort to surrogate fuels such as RFO which helps cut down production cost. This action comes with attendant consequence of deposit formation in nozzle tip, inability of the generating set to re-start after shutdown, and subsequent deterioration of injector nozzle/failure of injector nozzle. It then becomes imperative to identify factors which contribute to the spray behaviour of RFO when used as a surrogate fuel in diesel engine. Hence, this study is aimed at investigating the effect of fuel physical properties on the spray parameters of RFO.

Research Elaborations

Spray parameters are categorized as Macroscopic and Microscopic spray parameters. Macroscopic spray parameters indicate the relationship between the spray and the combustion chamber where the injected spray mixes with air. These macroscopic parameters include: Spray tip penetration, Spray cone angle, Spray volume, and Spray area. Microscopic spray parameters give an insight into the atomization pattern of the fuel. Microscopic spray parameter includes Sauters medium diameter (SMD).

Spray tip penetration: Dizayi, *et. al.*, [1] defines the spray tip penetration as the maximum distance for the spray to extend before reaching the walls of the combustion chamber. The analysis of the spray length penetration is very useful to determine the geometric design of high speed diesel engine combustion chambers with direct injection. [2]

Spray cone angle: Agarwal and Chaudhury, [3] defines spray cone angle as the largest angle formed by two straight lines from the nozzle hole to the spray in the combustion chamber. Martinez, *et. al.*, [2] noted that increase in the spray angle reduces the spray penetration while excessive penetration is favoured when the angle decreases lower than certain values, causing the spray to collide with the piston bowl or combustion chamber.

Spray area: it indicates the extent which the spray spreads across the combustion chamber. [4] opines that the spray area is dependent on the outline of each spray and is a representation of the quality of the air-fuel mixture. Furthermore, the spray area is for a penetration value and a given density of the injection environment independent of the injection pressure. It is affected by the cone angle and density ratios.

Spray volume: the spray volume depends on the spray penetration and cone angle. The larger the cone angle and spray penetration, the larger the spray volume. [4]

Sauters Medium Diameter (SMD): The SMD characterizes the atomization performance of a fuel. It is a factor that helps determine the combustion range and pollutant exhaust emissions, because the mechanism of atomization ensures even distribution of the droplets in the injection process. According to, [2] the quality of the atomization of a liquid spray can be estimated on the medium diameter of the droplets which defines the characteristics of a population of drops present in a sample. In some processes, SMD is used, to represent the diameter of droplets which have the same volume/surface relation in the totality of the spray, as well as the arithmetic average diameter.

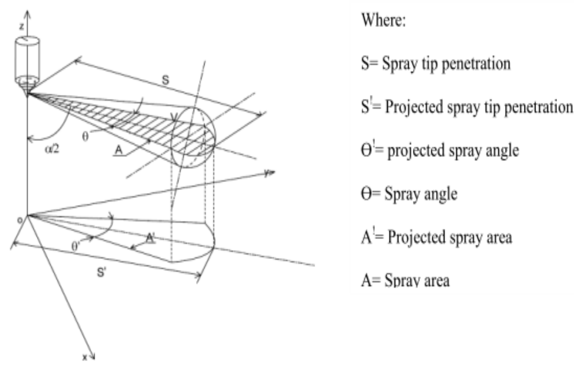

Figure 1: Macroscopic Spray Parameters of a diesel injector spray (Delacourtet. al., 2005)

Researches have shown that physical properties of fuel such as viscosity, density, and surface tension affect the macroscopic and microscopic spray of a fuel. For instance, [5] carried out a study on spray and combustion characteristics of gasoline and diesel in a direct injection compression ignition engine. The aim of the study was to investigate the physical mechanism and relationship for the spray and combustion characteristics under non-evaporating and evaporating conditions. The result under non-evaporating condition shows that the liquid penetration length of the diesel and gasoline was very similar without a marked difference especially at high injection pressure. The gasoline exhibited a slightly shorter liquid penetration length compared with diesel. The study attributes this observation to gasoline’s lower density and viscosity properties compared to diesel. The spray cone angle was initially high but decreased rapidly to 200μs after Start of Ignition (SOI), and then converged to a certain value. After converging to a certain value, [5] noted that the spray cone angle increased; also, the gasoline spray presented a larger spray cone angle with the diesel spray. The spray cone angle for gasoline ranged from 22° to 26° while it was 17° to 22° for diesel with varied injection pressures. Under evaporating condition, the study reveals that gasoline spray exhibited significantly shorter liquid penetration and it was approximately half that of diesel spray. This resulted from the superior vaporization characteristics of gasoline.

Mohan, *et. al.*, [6] carried out a study on the spray characteristics of ether fuels based on numerical simulation. The ether fuels investigated are dimethyl ether (DME) and diethyl ether (DEE). The study focused on numerical study of the cavitation characteristics of ether fuels and its effect on spray development process. The study reveals that the spray penetration of diesel fuel is comparatively longer than ether fuels. This is due to high higher viscosity and density possessed by diesel. Similarly DEE shows longer penetration than DME for the same reason.

While carrying out a spray simulation study on dimethyl ether (DME) and diethyl ether (DEE) fuels, [6] observed that the droplet size decreasing rate for ethers (when compared to diesel fuel) are much higher because of various properties like low viscosity, high vapour pressure and low surface tension. Nevertheless, the droplet size of DEE is higher compared to DME because of its relatively higher surface tension. The study revealed that though atomization of diesel and ether fuels behave similarly, the level of atomization differs between them. Ether fuels are atomized better since they are characterized by higher Reynolds number and lower Ohnesorge number compared to diesel for same injection pressure. [6] opined that the higher Reynolds number signifies high turbulence and aerodynamic forces on droplets which help in finer droplet formation. Also lower Ohnesorge number signifies low viscosity and low surface tension which means smaller droplet sizes. The excellent atomization behaviour of Ether fuels compared to diesel fuel aid in better air fuel mixing and ensures clean and proper combustion.

Selvan, *et. al.*,[7] studied the atomization pattern within the spray breakup region and observed that the Reynolds and Weber numbers both increased for diesel and Jatropha Oil Methyl Ester (JOME) with increasing the injection pressure, but diesel recorded higher values than JOME. This is due to the higher density and viscosity of JOME. The result implies that diesel will show a higher atomization because of high turbulence it will exhibit due to its higher Reynolds number.

Dizayi, *et. al.*, [1] investigated the SMD of an Ultra Bio Fuel (derived from used cooking oil), diesel oil and blends of UBF with diesel oil at different engine speeds and injection timings taking into account the piston crown cavity size as a limit for the maximum jet penetration length. The study concluded that the practical consequences for the larger SMD is a limited fuel to air contact and a greater temperature gradient from the surface to the centre of the droplet which affects fuel evaporation and mixing with air. A more heterogeneous mixture with longer ignition delay period is expected.

Wang, *et. al.*, [8] in a comparative study of SMD of biodiesels and pure diesels concluded that biodiesels generate larger SMD due to higher viscosity and surface tension.

These researches cited all allude to the fact that physical properties of fuel such as density, viscosity, and surface tension play important roles in the spray behaviour of any fuel. A lower density and viscosity value will lead to shorter spray penetration length, while a higher density and viscosity value will lead to a longer spray penetration length and spray area. In the latter, increase in the spray volume will ensue because the spray volume is dependent on the spray length. Also, the SMD of a fuel is determined by the viscosity and surface tension of the fuel.

MATERIALS AND METHOD

RFO Sourcing: In Nigeria, the source of RFO used in most industries that rely heavily on diesel engine powered electric generator is mostly from private refining companies such as Niger Delta Petroleum Resources (NDPR) located at Ogbelle in Rivers state, and sometimes the bunkering activities carried out within the Niger Delta regions of the country. In this bunkering process, crude oil is diverted from oil pipelines and refined in a provisional facility with inadequate set up for proper distillation of crude oil. As a result, the crude oil is not properly distilled and some fractions of diesel and heavy gas oil are present in the RFO obtained. Although RFO varies in composition from one geographical location to another, this bunkering phenomenon and the product from refining companies account for the various quality/composition of RFO obtained from a particular facility or across similar facilities within the Niger Delta region.

Mode of Experiment: Fuel (sample unit) was collected from an industry running on the RFO after it had gone through the processes of decantation, heating and filtration and filled into a tank. With the aid of an electric motor, the high pressure pump is energized to provide and maintain the high injection pressure needed by the common rail injector. An Injector tester unit is installed between the common rail injector and the piezo-electric fuel injector so as to determine the amount of fuel to inject into the CVSC per time. A visualization opening of 90mm is made in the CVSC and covered with quartz. As light from the Xenon lamp passes through the lens and falls on the spray, the changes in density between the air and the spray in the CVSC experienced by the light rays causes a change in the local refractive index. This refracted image produced was captured by the CCD camera and recorded using the computer system. The images recorded are processed and used to determine the spray parameters under investigation.

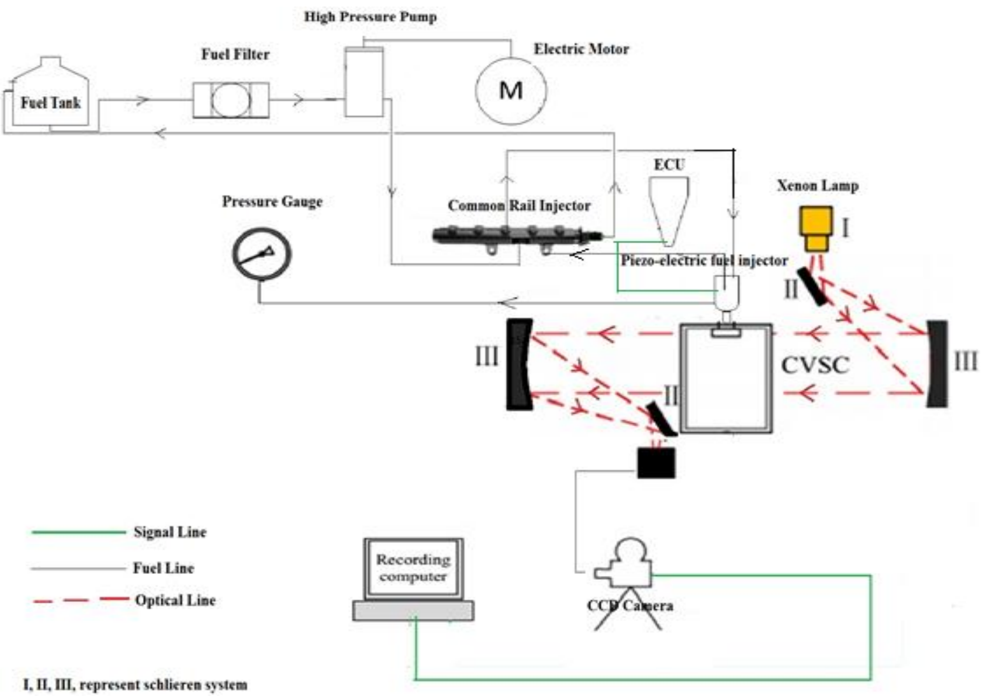

Figure 2: Experimental layout for schlieren visualization technique.

Characterization of oil: The RFO was characterized to determine the physicochemical and thermal properties of the oil, and the result is presented in table (1).

Table 1: Specifications of test fuel

Parameter	Value
Viscosity @ 28°C (mPa.s)	9.161
Density (kg/m^3)	867.9
Water content (%)	20.88
Acidity (mg/l)	18.04
Cloud point (°C)	5
Flash point (°C)	69.48
Smoke point (°C)	74.30
Fire point (°C)	94.65
Boiling point (°C)	209.86
Specific heat capacity (kJ/kg°C)	1.88
Cetane number	37
Salinity ppt	0.9735
Pour point (°C)	-4

Since viscosity varies with temperature, the fuel was heated in order to determine the corresponding viscosity within intervals of 10°C before the fire point. The varying temperature and its corresponding viscosity value is presented in table 2.

Table 2: Result of Viscosity against Temperature

Viscosity (Pa.s)	Temperature (°C)
9.16×10^{-3}	28
5.01×10^{-3}	38
4.28×10^{-3}	48
3.60×10^{-3}	58
3.56×10^{-3}	68
3.54×10^{-3}	78
3.54×10^{-3}	88

RESULT AND DISCUSSION

Spray visualization and processed images: Raw and processed images obtained from the schlieren visualization set up are presented in Figures 2and 3.

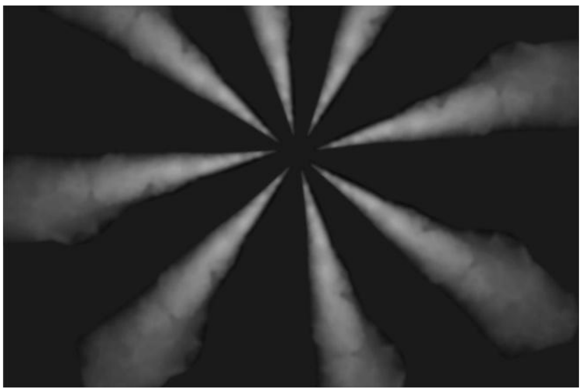

Figure 3: Processed spray image with a subtracted background and extracted spray plume.

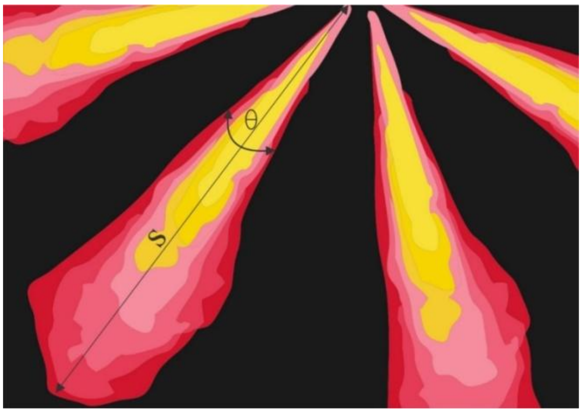

Figure 4: Determination of spray length and spray cone angle.

Effect of Viscosity and Surface tension on Spray tip penetration length

The experiment carried out to determine the effect viscosity and surface tension has on the spray length against various injection time shows that the spray tip penetration length of the fuel increases with increase in time of injection. Also, changes in the spray penetration length are proportional to changes in viscosity. In other words, reduction in the fuels viscosity leads to reduction in the spray penetration length. For instance, in figure 5, at a time of injection (ToI) of 500 µs, for 9.161 mPa.s, the spray penetration length is noted to be within the 400mm – 600 mm range. As the viscosity decreasesto3.54 mPa.s, the penetration length also decreases to a value less than 200 mm.

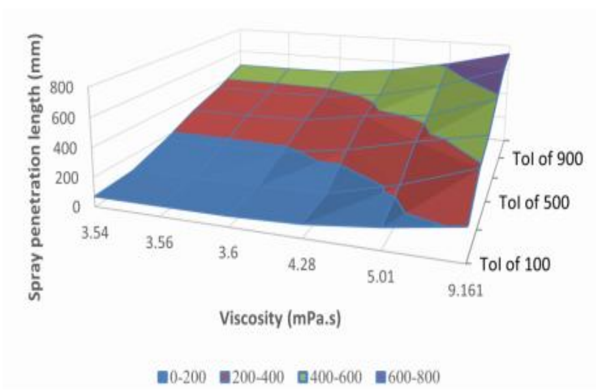

Figure 5: Variation of Spray penetration length against Viscosity.

This observation occurs due to the weakening of the cohesive forces of the fuel as viscosity reduces. Therefore, at higher viscosity values, longer spray lengths are expected which will lead to splashes on the cylinder walls, and subsequently poor combustion because the engine will be running on a rich fuel mix after start-off conditions.

Effect of Viscosity and Surface tension on Spray cone angle

Result of the spray cone angle for RFO revealed that the relationship between the viscosity and spray cone angle is inversely proportional at higher viscosity values and increases monotonically at lower viscosity values with the range of diesel fuel. This is so because as the forces of cohesion in the fuel are weakened, the fuel molecules acting under the injected pressure become less localized, and tend to diverge. This phenomenon occurs when the viscosity of RFO approaches that of diesel.

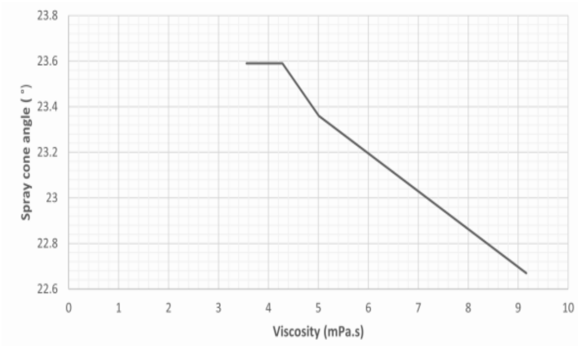

Figure 6: Spray cone angle versus Viscosity.

Effect of Viscosity and Surface tension on Spray area

The spray area was noted to be independent of the viscosity and surface tension as there was a monotonic change in the spray area with either an increase or decrease in viscosity. However, it was observed that a relationship exists between the spray area and the time of injection. Figure 7 allude to the proportionality of the relationship that exists between the spray area and the time of injection.

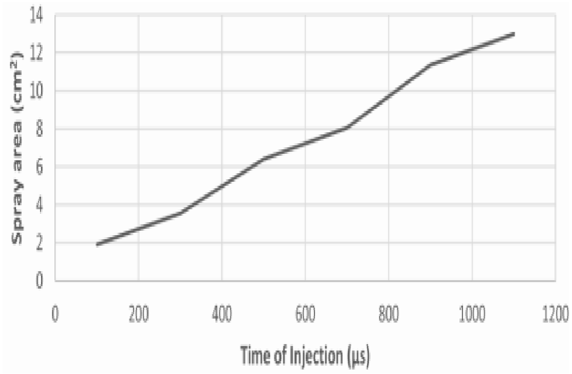

Figure 7: Variation of Spray area against Time of Injection.

The reason for its monotonic change as it regards viscosity is because, the spray area is influenced by the spray cone angle; hence, the monotonic relationship which exists between the spray cone angle and viscosity transcended to the spray area.

Effect of Viscosity and Surface tension on Spray volume

The spray volume was not affected by changes in the fuel viscosity and surface tension, rather, it was influenced by the time of injection. The spray volume increases with increase in the injection time. Figure 8 show that the relationship between the spray volume and the injection time is proportional. This phenomenon is expected as the time of injection indicates how long the injector nozzle valve will stay open. Therefore, the more the open condition duration, the more the volume discharged. Also, the independent condition of the spray volume towards the viscosity of the fuel is owing to the monotonic relationship that exists between the spray cone angle and the viscosity.

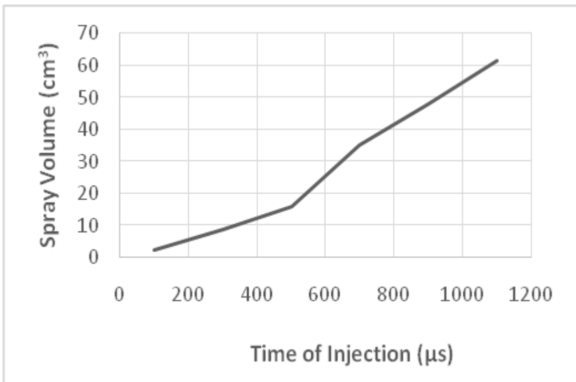

Figure 8: Variation of Spray volume against Time of Injection.

Spray tip velocity

The spray velocity was noticed to depend on both the time of injection, viscosity and surface tension. The experimental result reveals that a proportional relationship exists between the spray velocity and the viscosity of the fuel at early spray stages. As the spray progresses, the frictional drag of the liquid droplets lead to a loss in its kinetic energy which translates to less energetic molecules and subsequently lesser spray velocity. Figure 9show that there is a decrease in the spray velocity for all the various viscosity values as the injection time increases.

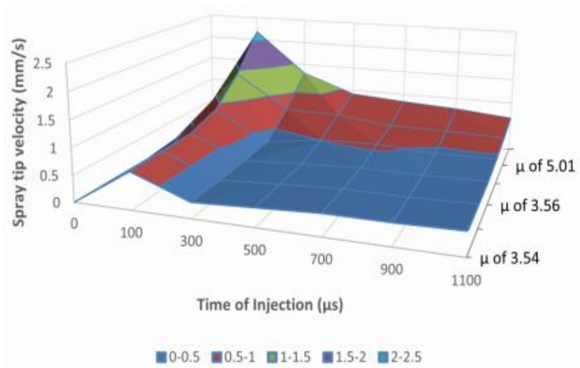

Figure 9: Variation of Spray velocity against Time of Injection for various values of Viscosity

The spray velocity was noted to be proportional to the changes in viscosity of the test fuel. Therefore, an increase or decrease in the viscosity will lead to a corresponding increase or decrease in the spray velocity. Figure (10) portrays the variation in the spray tip velocity with viscosity.

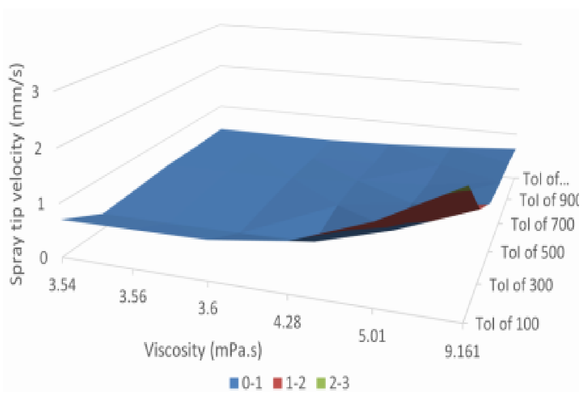

Figure 10: Variation of Spray velocity against Viscosity for various values of Time of Injection

Effect of Viscosity and Surface tension on Sauter Mean Diameter (SMD)

SMD characterizes fuel atomization; this mechanism of atomization ensures even distribution of the droplets in the injection process. Thereby, determining the combustion range and pollutant exhaust emissions. Due to the inadequacy of the schlieren technique in determining microscopic spray parameters, the equation established by [1] was used to generate a Simulink code block in MATLAB to determine the fuel SMD.

$$SMD = 9.57 \times V_{act}^{-0.37} \times \rho_a^{0.21} \times \rho_f^{0.28} \times e^{0.03 v_f}$$

Where: $V_{act} = C_d V_{th}$; $V_{th} = \left[\frac{2\Delta P}{\rho_f}\right]^{0.5}$, ρ_f and ρ_a = density of injected fluid and density of working gas fluid respectively.

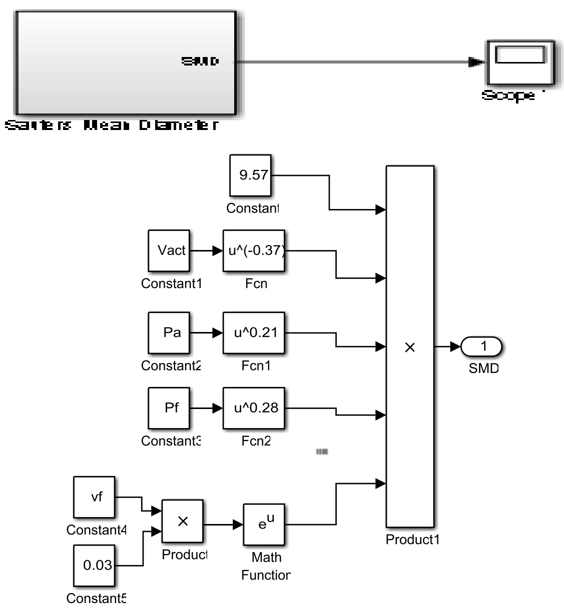

Figure 11: Code blocks for the determination of the spray Sauter Mean Diameter.

It was observed that the SMD is did not vary for the various values of viscosity investigated. The SMD gives the atomization capacity of the fuel. The lower the SMDvalue, the better the atomization of the fuel. The fuel had an atomization value of 2.85 mm. When compared with diesel which is 0.715 mm, [9] it is seen that its atomized size is nearly four times higher than conventional diesel fuel. This observation is due to its high viscosity and surface tension values. As a result of this, a more heterogeneous mixture with longer ignition delay period is expected.

CONCLUSION

The study focused on the effect of fuel physical properties on spray parameters of RFO. The following conclusions were drawn from the study.

- Viscosity of RFO is higher than viscosity of conventional diesel, with RFO having longer penetration length than diesel, and changes in the spray penetration length of both fuels is proportional to changes in viscosity.
- RFO has a larger spray cone angle than diesel fuel, and the relationship between the viscosity and spray cone angle is inversely proportional at higher viscosity values and increases monotonically at lower viscosity values for both fuels.
- The spray area is independent of viscosity due to the monotonic change in the spray area with either an increase or decrease in viscosity. However, a proportional relationship exists between the spray area and the time of injection.
- The spray volume for both fuels is not affected by changes in the fuel viscosity. Rather, it is influenced by the time of injection. The spray volume increases with increase in the injection time.
- The spray velocity depends on both the time of injection and viscosity. From the experimental result, a direct proportional relationship exists between the spray velocity and the time of injection at early spray stages. As the spray progresses, the frictional drag of the liquid droplets leads to a loss in its kinetic energy which translates to less energetic molecules and subsequently lesser spray velocity.
- Spray parameter values of RFO are higher than those of diesel fuel.
- The higher spray parameters values of RFO will lead to a higher spray volume causing the spray to impinge on the walls of the cylinder. As a result of the excess fuel present, the engine continues to run on a rich mixture after initial start-up conditions.
- The SMD of RFO was constant for the values of viscosity considered, and found to be almost four times higher than diesel fuel.
- As a result of this, a more heterogeneous mixture with longer ignition delay period is expected.

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