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Effect of silver nano-particle blended biodiesel and swirl on the performance of diesel engine combustion

Nagaraj Banapurmath[1], T. Narasimhalu[1], Anand Hunshyal[2], Radhakrishnan Sankaran[3], Mohammad Hussain Rabinal[4], Narasimhan Ayachit[5], Rohan Kittur[1]

[1]Department of Mechanical Engineering, B. V. B. College of Engineering and Technology, Hubli-580031, India
[2]Department of Civil Engineering, B. V. B. College of Engineering and Technology, Hubli-580031, India
[3]Nehru College of Engineering and Research Centre Pampady, Trissure (Dist), Kerala, India
[4]Department of Physics, Karnatak University, Dharwad, Karnataka, India
[5]Department of Physics, Rani Channamma University, Belgaum, Karnataka, India

Email address:

nr_banapurmath@rediffmail.com (N. Banapurmath), narasimhalu.t.n@gmail.com (T. Narasimhalu), amhunashyal@bvb.edu (A. Hunshyal), ngpcradhakrish@yahoo.co.in (R. Sankaran), mkrabinal@rediffmail.com (M. H. Rabinal), (nhayachit@gmail.com (N. Ayachit), rohan_kittur@yahoo.co.in (R. Kittur)

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Abstract: Increased energy requirement in sectors like transportation, power generation and others coupled with depletion of high energy non-renewable energy resources like petroleum products and their harmful tail pipe emissions has led to search for new alternative and renewable energy resources. Different methods have been adopted to reduce tail pipe emissions and these include engine modification, fuel alteration, and exhaust gas treatment. Low emission characteristics and equivalent energy density of biodiesel are useful for replacement for petroleum fuels in internal combustion engines. Recently addition of catalytic reactivity materials like metal and oxide materials to biodiesel and their effect on engine performance has been reported in the literature. Due to their special properties like higher thermal conductivity, chemical and electrical properties enhanced properties of the base fuel diesel/biodiesel when these additives were used has been reported. In the present work both engine modification as well as fuel alteration techniques have been adopted to study their effect on diesel engine performance and emission characteristics. Engine modification involved provision of tangential slots on the piston crown surface. Fuel modification included addition of metal and metal oxide nano-particles to Honge biodiesel called Honge Oil Methyl Ester (HOME) as an alternative fuel for diesel engine applications. Experimental investigations were carried out to determine performance, emission, and combustion characteristics of diesel engine operated on diesel, HOME and HOME-silver nano-particles blended fuels. The biodiesel was prepared from honge oil called Honge Oil Methyl Ester [HOME]. The silver nano-particles were blended with HOME in the mass fractions of 25ppm and 50ppm using a mechanical homogenizer and an ultrasonicator. Subsequently, the stability characteristics of silver nano-particles blended–biodiesel fuels were analyzed under static conditions for their homogeneity. A considerable enhancement in the brake thermal efficiency with substantial reduction in the harmful pollutants from the engine for the nano-additive biodiesel blends was observed. Maximum brake thermal efficiency was obtained for HOME+ 50SILVER with reduced harmful pollutants compared to HOME+25SILVER blends. With swirl intended slots provided on the piston crown surface the performance was further improved using HOME+50SILVER in general and for 6.5mm slot on the combustion chamber in particular.

Keywords: Diesel Engine, Silver Nano-Particle, HOME, Biodiesel, Ultrasonicator, Combustion, Emission

1. Introduction

Depletion of fissile fuel resources, their harmful emissions when used in engines and increased energy requirement for sectors like transportation, energy generation has resulted in a need to search for new alternative energy sources. The increased environmental pollution and stringent emission norms are considered to be the main reason for need of new energy source. Many researchers have made attempts to increase the engine efficiency and decrease pollutants from engine exhaust using different methods of engine modification as well as fuel alteration.

1.1. Nano-Particles as Additives

Addition of some metal and metal oxide in the form of nano-powder to the base fuel may enhance the properties of the fuels. This is due to the interesting properties of nano-particles like higher specific surface area, thermal conductivity, catalytic activity and chemical properties as compared to their bulk form. Many researchers have used nano-particles as additives in diesel as well as biodiesel as new hybrid fuel blends (Williams & Van den Wildenberg 2005)1. They reported properties of nano-particles such as size, thermal conductivity and chemical properties affect the performance and emission characteristics of engine. Reduced size of the nano-particles increased specific surface, surface to volume ratio, and surface area improving catalytic reactivity and magnetic properties as compared to their bulk form. Hence metal and metal oxide nano-particles addition to biofuel will improve the performance as well as reduce the harmful gases from engine exhaust (Jones et al. 2011)2. Adding aluminium nano-particles to ethanol and diesel as well as to biodiesel may enhance the ignition properties, faster burning, reduced incomplete combustion and ignition delay with heat built up in the fuel due to reactive nature of aluminium nano-particles added (Kao et al. 2008; Allen et al. 2011; Tagi et al. 2008; Basha and Anand 2010)3,4,5,6. Addition of cerium oxide nano-particles to biodiesel may also be effective as they enhanced surface area to volume ratio. Flash point of biodiesel, which is an indication of the volatility, was found to increase with the inclusion of such additives making them safer fuels. The viscosity of biodiesel was found to increase with the addition of cerium oxide nano-particles to biodiesel. The viscosity and the volatility were found to hold direct relations with the dosing level of the nano-particles (Sajith et al. 2010; Selvan et al. 2009)7,8. Performance and emission characteristics of a diesel engine operated on CNT- diesel blends have been experimentally investigated. Substantial enhancement in the brake thermal efficiency and reduced harmful pollutants were reported for such nano-additive-biodiesel blends compared to jatropha biodiesel and diesel. This could be due to better combustion associated with such novel hybrid nano-liquid fuel blends when used in diesel engines (Sabourin et al. 2009)9. Therefore, nano-particles can function as both catalyst and an energy carrier when used in base fuels in diesel engines. In addition, small scale of nano-particles, also facilitate stability of fuel suspensions when used with base fuels (Basha and Anand 2011)10.

1.2. Swirl Effect in Combustion

Efficiency and harmful pollutants from internal combustion engines mainly depends upon the combustion of fuel occurring inside engine cylinder. To obtain a better combustion with lesser emissions in diesel engines, it is necessary to achieve a good spatial distribution of the injected fuel throughout the entire space (Risi et al. 2003)11. The swirl effect of air and resulting fluid motion can have a significant effect on air-fuel mixing, combustion, heat transfer, and emissions (Schapertons and Thiele 1986)12. At the time of air intake during suction stroke swirl motion is needed for proper mixing of fuel and air, while at the time of compression swirl effect will be decreased due to decreased angular momentum of air compared to intake time. When the piston moves towards Top Dead Centre (TDC), the slots (grooves) provided on the piston crown surface has a significant effect on air flow resulting in better mixing with injected fuel spray and better combustion. This cannot happen during the time of air intake. For a base line engine provided with tangential grooves on the piston and retarded injection timing decreased delay period and better mixing of air-fuel mixture was observed resulting in better performance with reduced emissions (Subba Reddy et al. 2013)13. Introduction of swirl by providing number of grooves viz., 3, 6, and 9 on the piston crown to study its effect on the performance of a direct injection diesel engine fuelled with karanja biodiesel has been reported (Bharathi et al. 2012)14. Increased brake thermal efficiency by 6.9% and reduction in smoke emission by 5.9%, NOx by 1.8%, and HC by 2.83% were obtained. The effect of swirl on combustion and emissions of a heavy duty-diesel engines has been investigated (Timoey 1985)15 and optimum level of air swirl minimizing soot has been obtained and reported to depend on engine running conditions. Over-swirling caused centrifugal action directing fresh air away from the fuel, resulting in incomplete combustion and there by increased soot formation has been reported (Tippelmen 1977)16.

2. Nano-Biodiesel Fuel Blends Preparation

For the present study Honge oil was selected as an alternative fuel for diesel as it was locally and abundantly available. It was then subsequently converted into its biodiesel using transesterification method. It is a well established method used for biodiesel production. The optimum parameters for better conversion were determined maximizing biodiesel yield (Banapurmath and Tewari 2008, 2010)17, 18.

2.1. Blending Methodology

The nano-particles blended honge biodiesel fuel is prepared by mixing the HOME and silver nano-particles with the aid of an ultrasonicator. The ultrasonicator technique is the best suited method to disperse the silver nano-particles in the base fuel, as it facilitates possible agglomerate nano-particles back to nanometre range. The nano-particles are weighed to a predefined mass fraction say 25ppm and dispersed in the HOME with the aid of ultrasonicator set at a frequency of 40 kHz for 30 minutes. The resulting nano-particles blended honge biodiesel is named as HOME+25SILVER. The same procedure is carried out for the mass fraction of 50ppm to prepare the silver nano-particles blended honge biodiesel fuel (HOME+50SILVER). For analyzing the stability characteristics of silver nano-particles blended HOME, the blends were kept in bottles under static conditions.

Figure 1. *Blended Fuels.*

Table 1. *Specifications of Silver nano-particles.*

Sl. No	Parameters	Silver nano-particles
1	Manufacturer	Sigma Aldrich, Bangalore
3	Average particle size (APS) – nm	<150 nm
4	Surface area (SSA) m2/g	385
5	Purity - %	99
5	Thermal conductivity –W/mK	429
6	Density g/cm3 (lit.)	10.49

Table 2 below shows the Properties of HOME-silver nano-particles blends that are determined by appropriate apparatus.

Table 2. *Properties of HOME-silver nano-particles blended fuels.*

Properties	Diesel	Home	Home+25silver	home+50silver
Density, kg/m3	840	875	895	900
Calorific value, kJ/kg k	42390	36100	35000	35500
Viscosity at 40ºC (cSt)	4.59	5.6	5.8	5.8
Flash point in ºC	75	187	160	158
Cetane number	45-55	40	-	-

2.2. Swirl Effect

Figure 2. *Piston crown surfaces showing slots of widths.*

Swirl as mentioned earlier assists in proper mixing of air and fuel inside the combustion chamber. In the present study swirl was induced by providing suitable tangential slots (grooves) of different widths on the existing hemispherical combustion chamber. The piston crown of 80 mm bore was suitably modified to accommodate four tangential grooves. These grooves were of different widths viz., 5.5mm, 6.5mm, and 7.5mm and each were having a constant depth of 2 mm. Figure 2 shows the images of piston with tangential slots.

2.3. Heat Release Rate Calculations

The heat release rate of the fuel causes a variation of gas pressure and temperature within the engine cylinder, and strongly affects the fuel economy, power output and emissions of the engine. It provides a good insight into the combustion process that takes place in the engine. So finding the optimum heat release rate is particularly important in engine research. During this work a computer program was developed to obtain the heat release rate. The heat release rate at each crank angle was calculated by using a first law analysis of the average pressure versus crank angle variation obtained from 100 cycles using the following expression given below:

$$Qapp = \frac{\gamma}{\gamma - 1}[PdV] + \frac{1}{\gamma - 1}[Vdp] + Qwall$$

Where,

Q_{app}	Apparent heat release rate (J)
γ	Ratio of specific heats Cp/ (Cp – $\bar{R}$)
$\bar{R}$	Gas constant in (J / kmol-K)
C_p	Specific heat at constant pressure (J / kmol – K)
V	Instantaneous volume of the cylinder (m3)
P	Cylinder pressure (bar)
Q_{wall}	Heat transfer to the wall (J)

The heat transfer was calculated based on the Hohenberg equation (Hohenberg 1979) given below and the wall temperature was assumed to be 7230 K (Hayes1986).

$$Qwall = h \times A \times [\ Tg - Tw\ ]$$

$$h = C_1\, V^{-0.06}\, P^{0.8}\, T^{-0.4}\, (\, V_P + C_2\,)^{0.8}$$

h	Heat transfer coefficient in W/m2 K
C_1& C_2	Constants, 130 & 1.4
V	Cylinder volume in m^3
P	Cylinder pressure in bar
T	Cylinder gas temperature in K
V_P	Piston mean speed in m/s
A	Instantaneous Area (m^2)

3. Experimental Set Up

***Figure 3.** Experimental Test Ring.*

***Table 3.** Specifications of test rig.*

Sl. No.	Engine specification	
	Parameters	**Engine**
1	Type of engine	Kirlosker make Single cylinder four stroke direct injection diesel engine
2	Nozzle opening pressure	200 to 205 bar
3	Rated power	5.2 kW (7 HP) @1500 rpm
4	Cylinder diameter (Bore)	87.5 mm
5	Stroke length	110 mm
6	Compression ratio	17.5 : 1

The experimental investigations were conducted in two phases. In the first phase, the various physicochemical properties of modified biodiesel blends were determined and compared with those of the base fuels. In the second step, extensive experiments were conducted to determine performance, combustion and emission characteristics of a single cylinder four stroke direct injection compression ignition engine fuelled with modified and base fuels. Figure 3 shows the schematic experimental set up used. The engine was always operated at a rated speed of 1500 rev/min. The engine had a conventional fuel injection system. Injector was provided with three holes each having an orifice diameter of 0.3 mm. The injector opening pressure and the static injection timing as specified by the manufacturer was 205 bar and 23^0 BTDC respectively. Eddy current dynamometer was used for loading the engine. The fuel flow rate was measured on the volumetric basis using a burette and stopwatch method. A piezoelectric pressure transducer was mounted with the cylinder head surface to measure the cylinder pressure. The emission characteristics were measured by using HARTRIDGE smoke meter and 5 gas analyzer during the steady state operation. The tests were conducted with diesel, HOME and HOME–silver nano-particle blends. The specification of the compression ignition (CI) engine is given in Table 3. Injection timing and injection pressure for diesel were maintained at 23^obTDC and 205 bar, while for HOME and HOME-Nanoparticle blended fuels it was kept at 19^obTDC, 230 bar. Engine was in turn run with the selected fuel combinations for different slotted pistons. Table 3 shows specifications of the engine used for present work.

4. Results and Discussion

This section explains the performance, emission and combustion characteristics of the diesel engine fuelled with novel hybrid fuel blends. Effects of nano-particle additives to HOME and swirl on the diesel engine performance is presented.

Effects of nano-particle additives to HOME:

4.1. Variation of Brake Thermal Efficiency

Figure 4 shows variation of brake thermal efficiency for diesel, HOME and HOME-silver nanoparticle blended fuels. The HOME resulted in inferior performance due to its higher viscosity (nearly twice diesel) and lower volatility and lower calorific value. However the brake thermal efficiency of the HOME-silver nano-particle blended fuels improved compared to neat HOME operation. This could probably be attributed to the better combustion characteristics of HOME-silver nanoparticle blends. In general, the nano-sized particles possess high surface area and reactive surfaces that contribute to higher chemical reactivity and act as potential catalyst. In this perspective, the catalytic activity of HOME-silver nano-particle could have improved due to the existence of higher surface area and active surfaces prevailing. The silver nano-particles provide higher surface area and higher thermal conductivity as compared to HOME. Moreover, in case of HOME+50SILVER the catalytic activity may be enhanced due to the high dosage of silver nano-particles compared to that of HOME+25SILVER. An increase in surface area in liquid fuel droplets due to the possibility of droplets somehow being formed on the nano-particles could also be responsible for this observed trend. These properties provide increased reactivity and faster burning rates of fuel. Due to this effect, the brake thermal efficiency was higher for HOME+50SILVER compared to that of HOME+25SILVER.

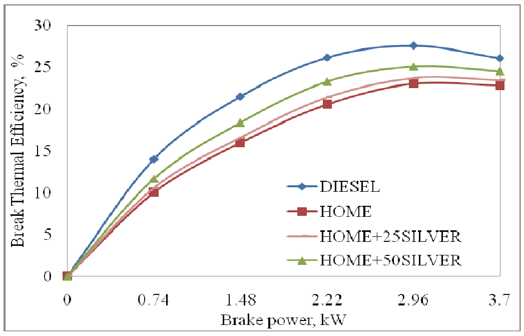

***Figure 4.** Variation of Brake Thermal Efficiency.*

4.2. Variation of HC Emission

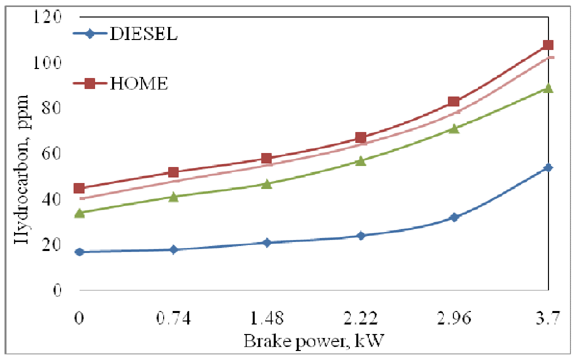

***Figure 5.** Variation of HC Emission.*

The un-burnt HC emission variations for HOME and HOME-silver nanoparticle blended fuels are shown in Figure 5. The HC emission for HOME operation was higher compared to diesel due to its lower brake thermal efficiency resulting from incomplete combustion. However HC emissions were marginally lower for the HOME-silver blended fuels compared to HOME alone operation. This could be due to increased catalytic activity and improved combustion characteristics of silver NPs which lead to improved combustion. HOME+50SILVER showed better performance with comparatively lower HC as compared to HOME+25SILVER due to the increased dosing level of silver nano-particles that provided higher surface area resulting in improved combustion characteristics.

4.3. Variation CO Emission

The CO emissions for diesel, HOME, HOME-silver blended fuel are shown in Figure 6. The CO emission for HOME operation was higher compared to diesel due to its lower thermal efficiency resulting in incomplete combustion. However CO emissions were marginally lower for the HOME-silver blended fuels than HOME. The higher catalytic activity and improved combustion characteristics of silver NPs and leading to improved combustion could be the reason for this performance. HOME+50SILVER showed the better results as compared to HOME+25SILVER fuel due to the increased dosing level of silver nano-particles that facilitates complete combustion of fuel inside the engine.

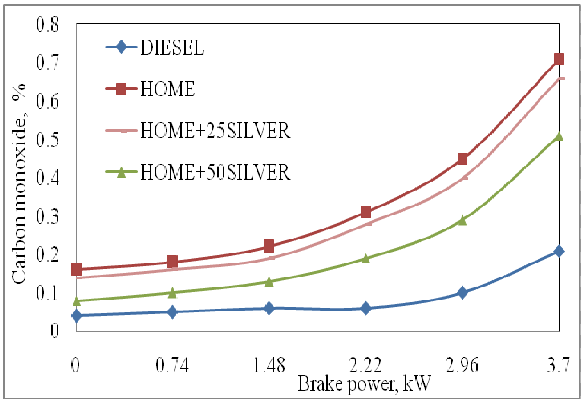

Figure 6. *Variation of CO Emission.*

4.4. Variation of Nox Emission

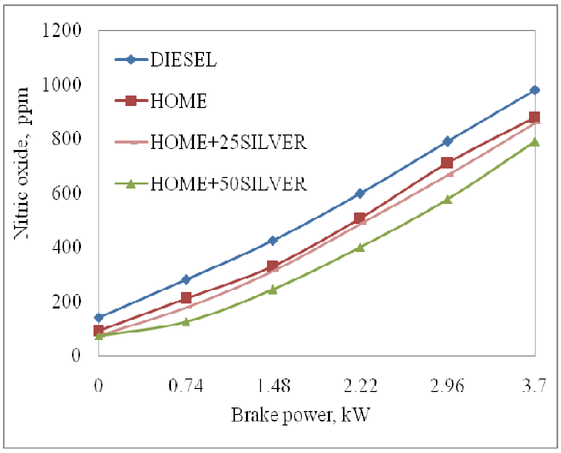

Figure 7. *Variation of Nitric oxides*

Figure 7 shows variation of NOx emission for diesel, HOME, HOME-silver blended fuels. HOME shows lower NOx emissions compared to diesel operation. Heat release rates of HOME were lower during premixed combustion phase, with lower peak temperatures prevailing inside the combustion chamber. Nitrogen oxides formation strongly depends on the peak temperature, which explains the observed phenomenon. Furthermore, HOME-silver nano-particles blended fuels produced lower NOx emission compared to that of HOME. This could also be due to higher premixed combustion observed with HOME- silver nano-particles blends. The HOME+50SILVER showed lower NOx compared to the HOME+25SILVER.

4.5. Cylinder Pressure

Figure 8 shows the variation in pressure with crank angle for HOME and HOME-silver nanoparticle blended fuels. Combustion started later in comparison to diesel with biodiesel and biodiesel silver nano-particle blended fuels. However increased catalytic activity observed with silver nano-particle blended biodiesel results in reduced delay period with combustion starting earlier as well.

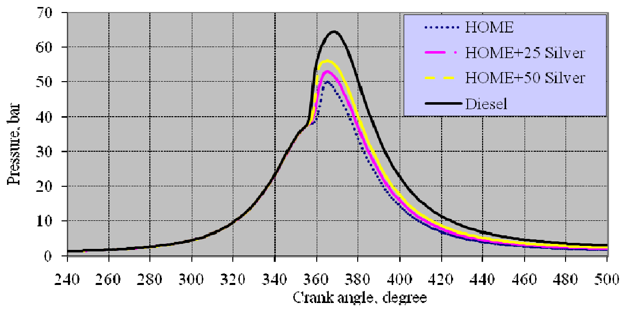

Figure 8. *Variation of cylinder pressure with crank angle for 80% load*

4.6. Heat Release Rate

Figure 9 shows heat release rate for nano-particle biodiesel fuel blends tested. It follows that for the biodiesel a shorter premixed heat-release portion occurs, in spite of their increased ignition delay. The heat release rate for HOME and HOME-silver nano-particles were lower compared to diesel operation. The reduced heat release rate during premixed combustion phase and increased heat release rate were observed during diffusion combustion phase for both HOME and HOME-silver nano-particles. This leads to increased exhaust gas temperature. With blend of silver nano-particles in HOME premixed combustion increased compared to HOME due to their increased catalytic activity, thermal conductivity and surface area.

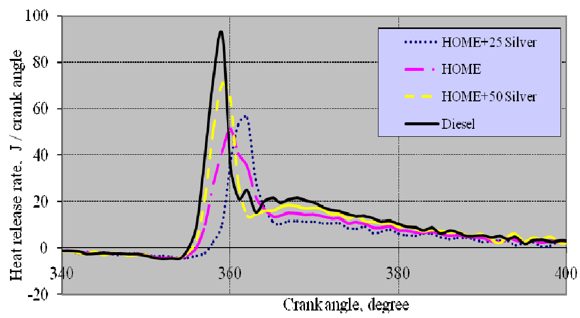

Figure 9. *Variation of heat release rate with crank angle for 80% load.*

5. Effect of Swirl on Diesel Engine Fuelled with Novel Hybrid Blends

In order to further improve the performance of diesel engine fuelled with HOME+50SILVER nano-particles, the swirl was created by inserting suitable slots on the hemispherical piston surface. Subsequently diesel engine performance and emission characteristics were obtained.

5.1. Variation of Brake Thermal Efficiency

Figure 10 shows variation of brake thermal efficiency for different slot widths provided on the piston surface using HOME+50SILVER blended fuels. The HOME+50SILVER with plain piston surface slot resulted in inferior performance. However brake thermal efficiency of the HOME+50SILVER blended fuels with swirl assisted by SLOTS improved compared to neat HOME+50SILVER operation. This could probably be attributed to the better mixing of fuel and air in the combustion chamber cylinder. The HOME+50SILVER+ 6.5mm slot showed improved performance as compared to the other two slots of 5.5mm and 7.5mm due to the better mixing effect induced by swirl and improved combustion of fuel.

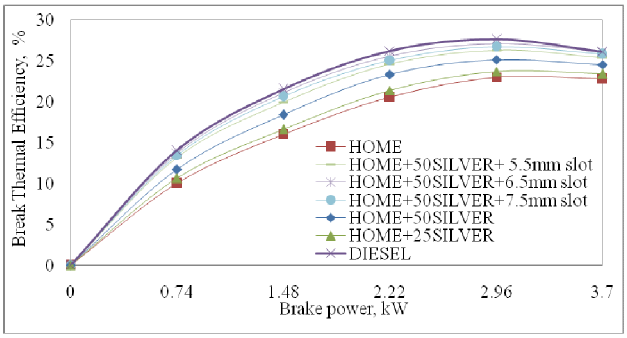

Figure 10. *Variation of Brake Thermal Efficiency*

5.2. Variation of HC Emission

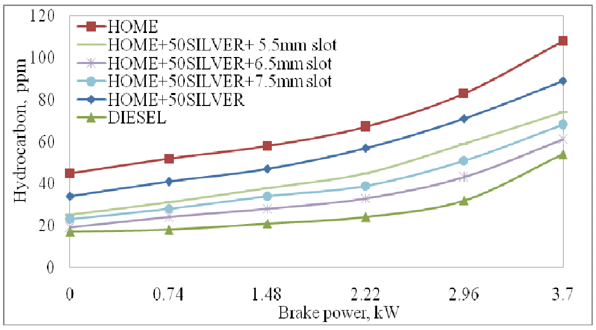

Figure 11. *Variation of HC Emission.*

The unburnt HC emission behaviour for different slot widths provided on the piston surface using HOME+50SILVER blended fuels are shown in Figure 11. The HC emission for HOME+50SILVER operation in all modes is higher compared to diesel due to its lower thermal efficiency. However HC emissions are marginally lower for the HOME+50SILVER+SLOTS blended fuels than HOME. This could be due to increased catalytic activity and improved combustion characteristics of silver NPs and better mixing of air-fuel in combustion chamber, which lead to improved combustion. The HOME+50SILVER+ 6.5mm slot showed lower UBHC emission as compared to the other two slots of 5.5mm and 7.5mm.

5.3. Variation CO Emission

The CO emission variations for HOME+50SILVER fuel combinations with and without slots on the piston surface are shown in Figure 12. The CO emission for HOME+50SILVER operation is higher compared to HOME+50SILVER+SLOTS due to its lower thermal efficiency with incomplete combustion. However CO emissions are marginally lower for the HOME+50SILVER+SLOTS blended fuels than HOME+50SILVER. The higher catalytic activity and improved combustion characteristics of silver NPs combined with swirl induction probably lead to improved mixing of fuel and hence in the resulting behavior. The CO emission of HOME+50SILVER+ 6.5mm slot was much lower than that of as compared to the other two slots of 5.5mm and 7.5mm.

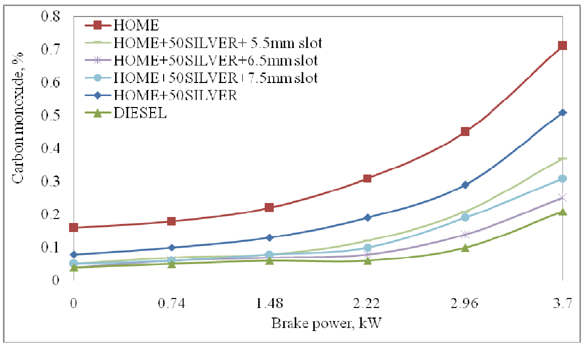

Figure 12. *Variation of CO Emission.*

5.4. Variation of NOx Emission

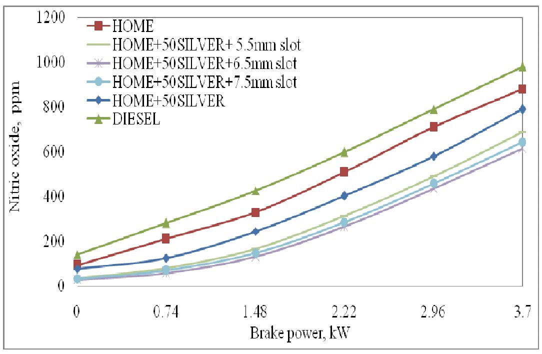

Figure 13. *Variation of NOx emission.*

Figure 13 compares variation of NOx emission for HOME+50SILVER fuel combinations with and without slots on the piston surface. The HOME+50SILVER showed lower NOx emissions compared to diesel operation. NOx emission of HOME+50SILVER+ 6.5mm slot was much higher than that observed for 5.5mm and 7.5mm slots. This could be due to more heat release rate obtained during premixed combustion for 6.5mm slot operation.

5.5. Cylinder Pressure

Figure 14 shows the variation in pressure with crank angle for HOME-silver nanoparticle blended fuels considering the effect of swirl. Combustion started later in comparison to diesel with biodiesel and biodiesel silver nano-particle blended fuels. However increased catalytic activity observed with silver nano-particle blended biodiesel coupled with swirl inducted resulted in reduced delay period with combustion starting earlier as well.

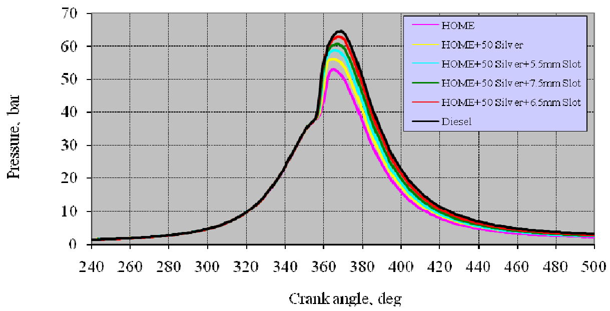

Figure 14. *Variation of cylinder pressure with crank angle for 80% load.*

5.6. Heat Release Rate

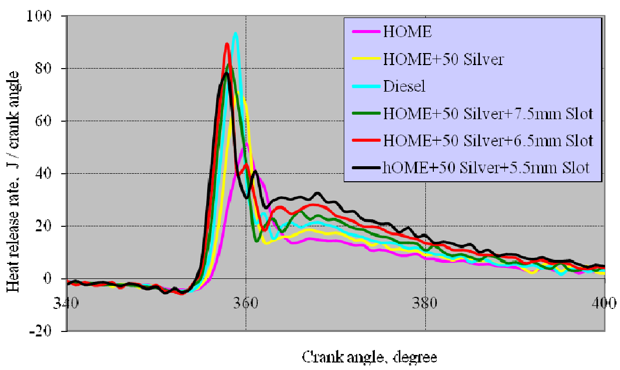

Figure 15. *Variation of heat release rate with crank angle for 80% load.*

Figure 15 shows heat release rate for nano-particle biodiesel fuel blends tested. It follows that for the biodiesel a shorter premixed heat-release portion occurs, in spite of their increased ignition delay. The heat release rate for HOME and HOME-silver nano-particles were lower compared to diesel operation. The reduced heat release rate during premixed combustion phase and increased heat release rate were observed during diffusion combustion phase for both HOME and HOME-silver nano-particles. This leads to increased exhaust gas temperature. With blend of silver nano-particles in HOME premixed combustion increased compared to HOME due to their increased catalytic activity, thermal conductivity and surface area. However increased catalytic activity observed with silver nano-particle blended biodiesel coupled with swirl inducted resulted in reduced delay period with higher heat release rates.

6. Conclusions

The performance, and the emission characteristics of HOME, HOME-silver nano-particles blended fuels with and without the effect of swirl were investigated in a single-cylinder, constant speed, direct-injection diesel engine. Based on the experimentation data, the following conclusions were drawn.

1. HOME resulted in poor performance in terms of reduced brake thermal efficiency. However HOME performance was enhanced with silver nano-particle additives. Performance was further improved with higher dosing level of silver nano-particles in biodiesel.
2. Increased HC and CO emissions were observed for HOME alone operation. Emission reduced drastically with silver nano-addition. Further reduction in these emissions obtained with increased dosage of nano-particles to HOME. NOx emissions were lower for nano-particle blended HOME.
3. Effect of swirl with tangential slots provision on the piston surface showed better results and reduced emissions. 6.5 mm slot was found to be optimum.
4. HOME+50SILVER+SLOTS showed lowered NOx emission.

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