Studies on Deposit Formation and Entrainment Characteristics of Urea in SCR System for Diesel and Biodiesel Exhausts

S. Sadashiva Prabhu*‡, Kapilan Natesan **, Nagaraj S Nayak ***

* Department of Mechanical and Industrial Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka, India-576104

** Department of Mechanical Engineering, Nitte Meenakshi Institute of Technology, P.B.No.6429, Yelahanka, Bangalore-560064

*** KBAT Technologies Private Limited, Pune, Maharashtra, India-411033

(ss.prabhu97@gmail.com, kapil_krecmech@yahoo.com, nagarajsnayak@gmail.com)

‡ Sadashiva Prabhu S; Tel: +91 9483648850, ss.prabhu97@gmail.com,

Received: 01.05.2022 Accepted:23.06.2022

Abstract- The Urea-Selective Catalytic Reduction (SCR) Technology is an after-treatment technique adopted by heavy-duty, diesel-run automobiles to meet stringent emission norms as conventional NH_3-SCR has handling problems of NH_3 in automobiles. Urea being in a hot environment decomposes and provides sufficient NH_3 to reduce NOx into N_2. At part loads, the engine exhaust temperature is low, which causes deposit formation in the Urea-SCR system and deposits to form complex non-depleting complexes. The variables affecting this deposit formation find their importance and mitigation of these deposits should be carefully done by controlling those variables. In this context, extensive work has been done earlier by authors using a hot air test rig. As actual SCR systems work with exhaust gases of actual engines, the phenomenological studies are verified using a single-cylinder diesel engine. The results obtained are in line with the trend of hot air conditions when compared with the earlier work of the authors. The SCR technology is presently successful in diesel-run vehicles and methods to evaluate and mitigate the deposits underway. The extension of SCR technology to biodiesel-run diesel engine vehicles is a future challenge as the biodiesel-fueled diesel engine results in higher NO_x emissions. A comparative study was undertaken in this work using a medium-duty diesel engine, and deposit formation characteristics are investigated in no-load and full conditions to reveal the quantitative analysis, and nature of deposits. It is found that the absorption of biodiesel by urea deposits inhibits further growth of deposits and entrainment characteristics. Studies are also extended to focus on entrainment characteristics and found that biodiesel inhibits entrainment characteristics.

Keywords Engine, NO_x, Selective Catalytic Reduction, Biodiesel, Entrainment.

Nomenclature

NO_x-Oxides of Nitrogen (NO and NO_2) ;PM-Particulate Matter; DPF-Diesel Particulate Filter; CYA-Cyanuric Acid EGR-Exhaust Gas Recirculation ;HPLC-High-Performance Liquid Chromatography; SCR-Selective Catalytic Reduction; SEM-Scanning Electron Microscopy; TGA-Thermogravimetric Analysis;UWS-Urea Water Solution; XRD-X-ray Diffraction;.IC-Internal Cobustion.

1. Introduction

The oxides of nitrogen (NO_x), sulfur dioxide (SO_2) and dust emissions are major pollutants when coal and diesel are burned to a larger extent in power plants and diesel-run vehicles [1]. The particulate matters (PM) and Oxides of Nitrogen (NO_x) are major pollutants from Diesel run automobiles. Most diesel engines are implemented with a Diesel Particulate Filter (PDF) as an after-treatment system to reduce PM. Further, PM accumulated in the regeneration process is burned to meet a regulatory requirement. Bio-diesel is an alternative fuel for IC engines despite the NO_x emission being in excess compared to diesel [2]. Excess emission of NO_x due to increased oxygen levels in the biodiesel blend [3, 4].

There are several methods to reduce NO_x of emitted gases from power plants, diesel engine exhaust, etc. One of them is urea-based Selective Catalytic Reduction (SCR), which is the most efficient method to reduce nitrogen oxides (NO_x) from these sources. As proven in power plants, SCR is again a promising technique for automobiles with the optimized combustion of fuel. End products are nitrogen, water, and carbon dioxide, which are harmless. Further, urea is not classified as hazardous to health.

In the SCR technique used for automotive diesel engines, Urea Water Solution (UWS) is sprayed to exhaust gases. The formation of NH_3 out of UWS droplets occurs through several stages, wherein droplets evaporate, and the solid urea undergoes thermolysis and decomposes into NH_3 and HNCO [5]. NO_x present in exhaust reacts with NH_3 over the catalyst and reduces to N_2. NO_x can be substantially reduced from lean diesel exhaust gases by using reduction techniques with the aid of catalysts. NH_3 reacts selectively with NO_x in the presence of oxygen to transform into N_2 and water vapor [5]. More details on chemical reactions and NO_x conversion over catalysts are found in the literature [6].

Despite this technology being implemented by some automobile companies, problems like wall deposition, localized corrosion due to urea deposits, lower NH_3 conversion efficiency, lower NO_x conversion efficiency, NH_3 slip, poisoning of catalyst, etc.

Diesel fuel with the current rate of consumption may exhaust in the near future. In that context, there is an increasing interest in using alternative fuels like biodiesel despite the known fact that increased NO_x [7, 8]. Extensive studies have been on SCR systems built for diesel engines operating with diesel found over 90% conversion of NO_x [9]. Urea injection into the exhaust stream of biodiesel reduces NO_x emission at the outlet with a non-catalytic method [10]. Additionally, some parametric studies reveal that NO_x alters with increased urea mass flow. Studies were also done on the effect of injection angle, the number of injector holes, mixing chamber diameter, etc. [10]. They do not deal with deposit formation characteristics at low temperatures with biodiesel.

Although the Urea-SCR system has proven efficient technique, the performance of the system and durability become paramount. In that context, factors affecting deposit formation should be identified, and measures to be taken. Studies done by some of the authors on deposit formation in various platforms are discussed subsequently.

Henrik Smith et al. [11] found that deposit growth has a linear relationship with time and areas of deposits remain the same with each experiment and shifting of the location of the deposits UWS injection rate increases. Sluder et al. [12] established that the Urea deposits were not found in the downstream region of the catalyst. Strots et al. [13] concluded that deposit formation is more prone to occur at temperatures ~200°C, low ambient temperatures (< -3°C), high UWS flow rate (≥0.15 g/s), and lesser mass flow rate of exhaust gases. Under these conditions, there is a possibility of 25-65% of injected urea turning into urea deposits.

Weeks et al. [14] observed the majority of deposits formed are urea at low temperatures. Thermogravimetric Analysis (TGA) studies reveal that pure urea and the deposits samples show that it will thermally decompose to Isocyanic acid (CYA) at 200°C. McKinley et al. [15] opined that atomization affects urea decomposition, thereby deposit and formation alter significantly. Zheng et al. [16] conducted experiments in two different environments; firstly, in hot air and secondly in hot air with NO_x. The identical deposits were observed in both cases with a small difference in quantity. However, experiments with air reach close approximation with actual diesel run situations.

Hyun An et al. [17] revealed that injector, injection angle and temperature of the exhaust gas significantly affect deposit formation or depletion. Xian et al. [18] concluded that injection pressure should be optimum for the SCR system for the optimized spray characteristics. The specific injection angle coordinates well with parameters like the velocity of the exhaust gas and gas temperature, for better uniformity of droplet distribution. More details on SCR reactions and route maps of the formation of various deposit compounds are detailed in the literature [19, 20].

It is required to do studies on various parameters that affect deposit formation, namely flow rate and temperature. Extensive studies were done by the authors using air in a hot air test rig [21]. Further, the authors also extended the study to various thermal treatments [22].

The above review clarifies that extensive research on deposit formation has occurred at low temperatures. Few studies were also found on diesel engines. However, limited studies are found on the usage of biodiesel-run engines. Few experimental works on biodiesel run engines found in the literature are focused on NO_x conversion rather than deposit formation with UWS injection without the catalytic converter [10].

Biodiesel blending is in practice but limited studies were found on deposit formation when engine runs with biodiesel and exhaust temperature is low for the case. Also, there are no studies found in the literature on entrainment aspects of UWS droplets when a diesel engine runs biodiesel blends. Furthermore, biodiesel-run engines have increased content of NO_x, owing to higher UWS requirements compared to diesel-run engines leading to requirements of over-dosage of UWS. These aspects are not covered in the literature. So, the study here was intended to urea deposition characteristics at low temperatures for diesel and biodiesel exhaust in the interest of their absorption and growth characteristics. The engine chosen was of low exhaust temperature, which gives maximum deposits with time, by which accelerated test conditions could be achieved. The growth urea deposits are gravimetrically analyzed at various sections on a timescale.

2. Methodology and Experimentation

The urea deposits at given load conditions are obtained in the exhaust, which is fitted with a stainless-steel pipe, along with flexible thin stainless-steel foils, that can be inserted and removed from the pipe easily. The foils can be intermittently removed and fixed back for weight analysis. The deposits are formed on foils after impaction by the injection of UWS. The deposits formed are gravimetrically analyzed. Initially, the test was conducted in a single-cylinder diesel engine for varying flow rates to check agreement with experimental results done by the authors on a hot air test rig [21]. Later, the study was extended to a 4-cylinder 4-stroke diesel engine running with diesel and biodiesel(Fig 1a). The deposits are collected in section- 1 and section-2 as shown in Fig.1b. Deposits collected are compared for two different running conditions (i.e. no-load and full load). The comparative study is extended further for the type of fuel and flow rate along with entrainment behaviour.

Table 1. Properties of UWS [22]

Density [kg/m^3]	1089
Boiling Point Temperature [°C]	104
Thermal Conductivity [W/m K]	0.57
Specific Heat [kJ/kg K]	3.4
Surface Tension [N/m]	0.0717
Latent Heat of Vaporization [kJ/kg]	2258

2.1. Properties of UWS and Fuels

In our study, we have used two fuels, i.e., diesel and biodiesel. The type of biodiesel used was Pongamia which is blended up to 10% with diesel. It has been recognized as "Biodiesel" because it contains saturated and unsaturated fatty acids with a proportion of 20.5% and 79.4%, respectively. Unsaturated fatty acid comprises fatty acids oleic acid (46%), linoleic acid (27.1%), and linolenic acid (6.3%). It contains fatty acids of low molecular weights such as lauric and capric acids in small fractions of 0.1% each [23]. Some of the properties are listed in Table 2 [23].

Table 2. Properties of Fuels

Property	Pongamia Oil Methyl Ester	Petroleum Diesel
Calorific Value	36050	42300
Viscosity (C St)	5.3	3.05
Specific Gravity	0.886	0.85
Cetane Value	51	47.8
Flash Point °C	147	56
Fire Point(°C)	153	63

2.2. Experimental Setup

Based on the basic velocity requirements, the exhaust pipe was chosen at approximately 75 mm was chosen. A diesel engine of a 407-pickup vehicle (Manufactured by Tata Motors, India) whose specifications as specified in Table 3 was used for the experiments with required additions fittings. At a temperature below 133°C, the evaporation of water occurs. The remnant urea is considered for deposit formation. As we are intended to check deposit formation at the low exhaust temperature of the exhaust gas, the chosen engine serves the purpose of extensive deposit formation as in the case of accelerated overdosed test conditions. A fabricated orifice meter is built near the engine exhaust to find the flow rate of the engine with suitable calibration.

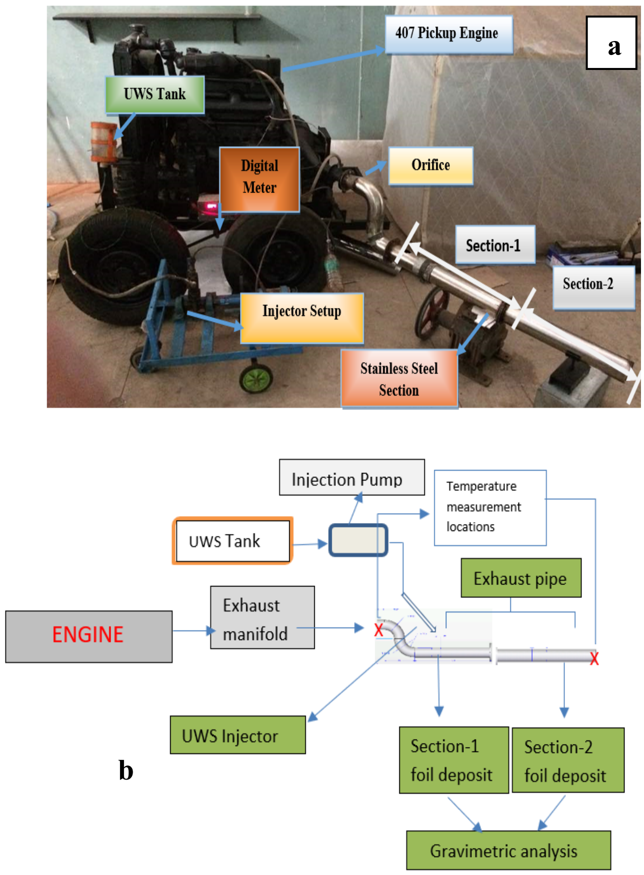


Fig.1. a) Experimental Setup b) Detailed diagram UWS injection and Deposit collection.

2.3. Urea Injection System

A motor-driven mechanically operated dosage pump and the injector are used to inject UWS at a minimum rate of 4 mL/minute at a frequency of 3 Hz. It is operated by an eccentric mounted on the camshaft of the reduction setup. The main objective of the injection system is to obtain UWS atomization to the required fineness, dosage, and spray penetration. An approximate method of finding UWS droplet size is followed and the methodology was explained by the authors in their earlier work [21] and droplet size is calculated as 150µm. Spring and plunger-type nozzles having a single orifice hole are used at the outlet. UWS is delivered with specified pressure, and the pressure is increased by decreasing orifice space in the nozzle.

Table 3. Specifications of Engine

Make	TATA
Engine	4SP Water Cooled
Power	55.2 kW @ 3050
Speed	1600 rpm
Engine cylinders	Four-cylinders
Displacements	2956
Fuel used	Diesel and

2.4. Exhaust Mixing Chamber

Stainless steel of grade 304 was used to fabricate the exhaust gas mixing chamber. Initially, the model was divided into two sections (0.55m and 0.45m) with TIG welded flanges at the end. Exhaust pipe in two sections enables easy insertion and removal of SS stainless steel foils. The fabricated exhaust gas mixing chamber is shown in Fig 1a with a dimension of 3" bore and 1m length.

2.5. Thermocouple with Digital Display

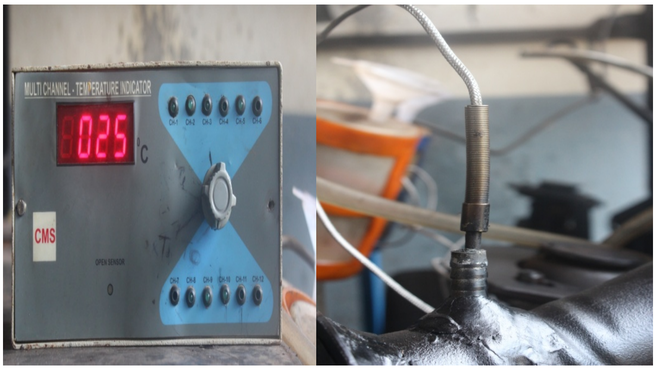


Fig. 2 a) Temperature Display b) Thermocouple

The thermocouple used is of type 'K' (Nickel-Chromium / Nickel-Alumel), with which temperatures up to 500°C can be measured. Special limits of error +/-1.1°C or 0.4%. It is connected to a digital display, which is shown in Fig.2 (a,b).

2.6. Orifice Meter Setup

An orifice meter is used to measure the flow rate of exhaust gas. The fabrication is done using TIG welding as shown in Fig 3(a, b) and the actual dimensions are given in Table 4. Later it was fabricated and calibrated, and the coefficient of discharge is calculated as 0.53. It is connected to a U-tube manometer with a water column to find the difference in pressures to evaluate the differential head.

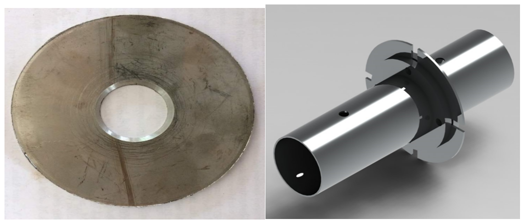


Fig. 3. a) Orifice plate b) Orifice meter design

Table 4: Parameters Considered for Designing

Exhaust Pipe Diameter, D	50.8 mm
Orifice diameter Do, 0.5D	25.4 mm
Differential Manometer, 0.5-1D P1 0.5D P2 1D	25.4 mm 50.8 mm
Orifice Plate Thickness	3 mm

2.7. Experimental Procedure

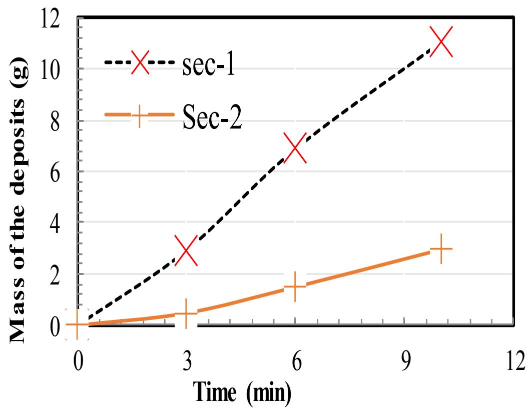
The procedure to conduct the experimentation is as follows. The diesel engine was run initially with diesel and was allowed to run for 10 min to reach steady-state condition at no-load condition. The temperature was measured using a thermocouple, and the pressure difference was measured using a manometer. The weights of sheet metal foils of section 1 and section 2 are taken using a digital weighing scale with the accuracy of ±10 mg and readings are noted down. Foils of section-1 and section-2 are inserted inside the respective exhaust pipe of sections. Urea water solution (UWS) is pumped into the hose of the injector nozzle for predetermined durations. The inserted sheet metal foils are taken out at time intervals of 3, 6, and 10 from the injection for weighing. The deposits collected on the sheet metal foils are noted by taking the difference in weights. Likewise, results are obtained for full load conditions. The temperatures at the injection points at region-1 and region-2 are much lower than the exhaust temperature at the manifold as they are away from the engine exhaust. Additionally, section 1 and section 2 are of pipes 3" in diameter which is larger than the actual engine manifold which leads to a drastic reduction in temperature. Temperature is recorded upstream of the urea injection point and exit of the pipe. The average values temperatures of two points are considered. These values are much lower than the actual engine exhaust temperature. The detailed procedure is shown in Fig.1b.

3. Results and Discussion

Extensive studies are seen in the literature about urea deposits in SCR systems, which mainly involve the characterization of deposits using EDX, HPLC, IR spectroscopy, XRD, NMR studies, etc. [19, 14, 24, 25, 26]. Extensive studies are done by the authors using hot air test rigs and deposits vary with temperature and flow rate [21]. The studies are done extensively on Pongamia oil Biodiesel for various blends on performance and other characteristics [27]. Authors opine the effect of the exhaust of biodiesel blend on deposit formation finds its importance

To ensure the same behavior in diesel exhaust, tests were carried out in single cylinder 4- stroke diesel engine of lower flow rate (not shown in the diagram) and it is further extended to 4-cylinder,4-Stroke medium-duty engine SFC 407 Four-Cylinder, 4-Stroke engine of higher flow rate. The deposits collected over the foils were taken for gravimetric analysis. In section 1, the deposits formed are due to the impaction of UWS and in section 2, the deposits are due to entrainment after impaction, droplet rebound, micro explosion, etc. Also, at a lower temperature, the deposits at section-1 and section-2 are the same by characterization, but they may vary at elevated temperatures. By considering parameters like mass flow rate, temperature, and types of fuel, we have studied the deposit formation characteristics concerning time in the present study.

3.1. Gravimetric Analysis deposits for Single-cylinder, 4-Stroke Engine



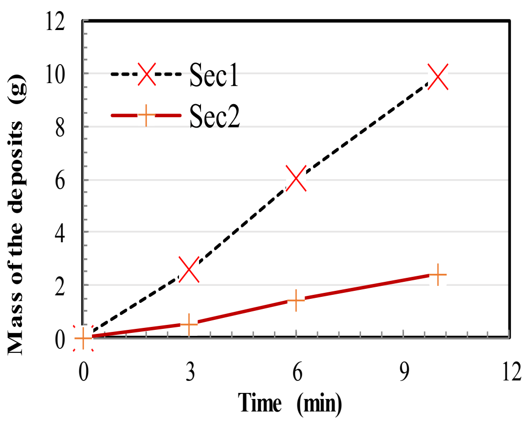


Fig. 4. a) No Load Condition at EGT 120°C- 21.26 kg/h b) Full Load Condition at EGT 180°C, 28 kg/h

The test was conducted by running the engine with diesel at zero and full load conditions. During no load, the maximum exhaust gas temperature is recorded at 120◦C. UWS is injected at 4 mL/minute to exhaust gas flowing at 21.2654 kg/h at an injection angle of 30◦. The deposits were collected for the cumulative time intervals of 3,6,10 minutes from both section 1 and section 2. The values are depicted in plots Figs. 4a, b. The experimental points are connected by a straight line to understand the growth stage-wise. It is observed in both section-1 and section-2 that for the initial 3 minutes, the deposits growth rate is slower and for the 2nd stage (3-6 min.) interval, the growth rate found increases and for the 3rd stage, it is slightly reduced compared to that of 2nd stage. During the start of the injection of UWS, the injection takes place on an overheated bare metal surface. There are phenomena like rebound and breakup, which increase the evaporation and decomposition of UWS, thereby hindering the deposit. However, once some precursor sites of deposits form, growth continues.

On the other hand, the foils cooled during the process of gravimetric analysis, and cooled foils change the deposit growth rate. A similar trend is observed when the engine runs at full load with increased exhaust gas flow rate and temperature. However, the deposits found with the reduction in quantity as flow rate and temperature effect pronounced. Authors could compare the results of a few operating points with results obtained from their earlier work [21] on a hot air test rig to identify the differences between deposit formation characteristics with air and diesel exhaust. The deposits obtained for 10 minutes at Exhaust Gas Temperature (EGT) at 180◦C at 28 kg/h is 11.17 g for diesel-run and the similar test on hot air at 200◦C and 34.74 kg/h is 12.29 g [21]. This reveals for two nearer operating points the fact that for similar conditions, there is a reduction in urea deposits for diesel exhaust compared to that of hot air. This indicates exhaust gas constituents have shown a significant effect in reducing deposit formation.

3.2. Gravimetric Analysis deposits for 407 Four-Cylinder, 4-Stroke Engine

3.2.1 When running with diesel

The second part of our studies was intended mainly on the effect of the type of fuel on deposit formation. We took a medium-duty 4-cylinder, 4-stroke, SFC 407 diesel engine as per specification and operated at no load (90◦C, 81.47kg/h) and full load conditions (110◦C, 90.45kg/h). The quantity of deposits varies according to temperature and flow rate even in this case. Further, observations are similar to the case of the single-cylinder engine, as discussed in earlier sections.

The test is conducted on a 4-stroke, 4-cylinder diesel engine and EGT 70-90◦C is attained with an exhaust gas flow rate of 81.47 kg/h and UWS is injected to exhaust gas at an angle of 30◦ to flowing direction with a UWS flow rate of 4 mL/min. The total deposit quantity (total amount of deposits of foil 1,2) after 10 minutes is 15.27g and it is found to increase. The deposits increased with quantity compared to the case of 21.26 kg/h at 120◦C as mentioned (in section 3.1) even though the flow rate was increased to 81.47 kg/h.

However, the growth rate remained with the same trend (Fig 5a). However, low-temperature effect low-temperature effect is substantial. So, deposits found increased even though the flow rate increased. Experiments were carried out at full load at 90.45 kg/h and found that the deposit quantity decreased as temperature and flow rate increased (Fig 5 b).

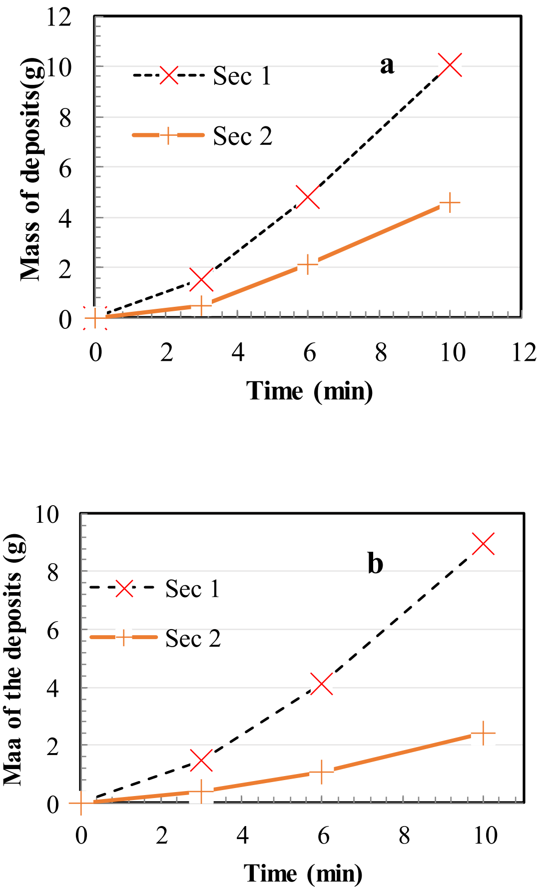


Fig. 5. Mass of deposits vs Time, when run with diesel (a) at EGT- 90C, 81.47 kg/h (b) at EGT- 120°C, 90.45kg/h.

3.2.2 When running with biodiesel

Experiments are conducted on a four-cylinder, four-stroke 407 diesel engine at no load (90°C, 81.47kg/h) and 100% load conditions (110°C with a mass flow rate of 90.45 kg/h). UWS was to exhaust gas at a rate of 4 mL/minute, and it is injected at 30° in a flowing direction. Fuel used is biodiesel blended up to 10%. The deposit formation behavior for no load and full load conditions is shown in Figs.6 (a, b). In the plot, deposit quantities are marginally decreased to 7.88g in foil-1 and 3.49g in foil-2 with reductions of 21.74% and 23.63%, respectively from the corresponding values of no-load conditions (Fig. 6(a)). It is evident by the observation that deposits of biodiesel exhaust decreased in both foil-1 and foil-2 indicating clearly the effect biodiesel blend on deposit formation.

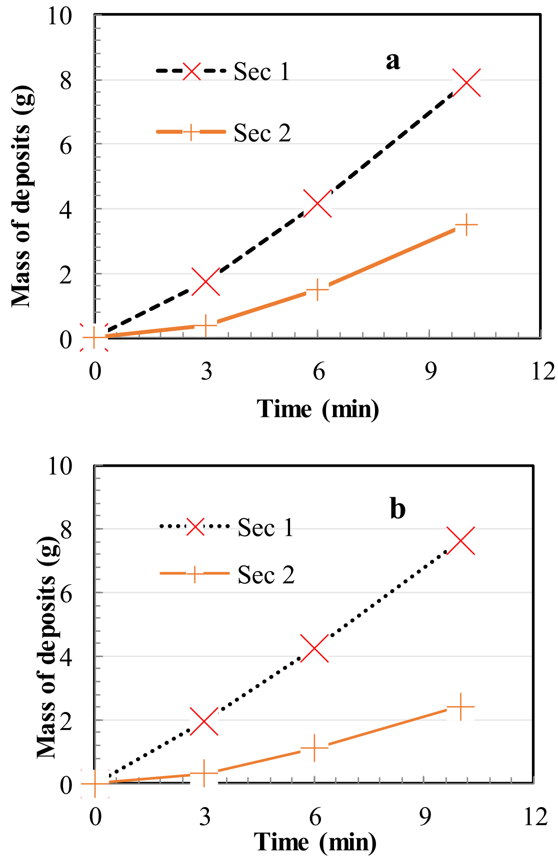


Fig.6. Mass of deposits vs Time, when run with biodiesel (a) at EGT- 90°C, 81.47 kg/h (b) at EGT- 120°C, 90.45kg/h.

After reaching the conclusion deposits decrease biodiesel run conditions, and the technical investigation finds its importance. Firstly, the unburnt hydrocarbon prone to deposit over the pipe walls gives differential surface interaction with UWS spray. Further, the adhesive characteristics are quite different over walls when exhaust gas characteristics change due to bio-diesel usage. Secondly, the pre-existing layer of urea deposits absorbs sufficient unburnt fuel content. This leads to a change in adhesive characteristics of the existing deposit layer for the fresh UWS spray. As a result, the UWS injected into the stream of exhaust gas of biodiesel will have different wall interactions. So, these interactions are quite different when compared to the same with the bare metal surface. The third aspect is the interaction of tiny droplets of spray with biodiesel-run exhaust. In addition, there is some evidence that the presence of incoming NO content in the exhaust gases decreases the deposition [16]. Accordingly, the presence of excess NO_x content in biodiesel exhaust leads to lesser deposits of urea.

3.2.3 Nature of deposits when diesel and biodiesel are used

To understand the effect of fuel used on the nature of deposits, the deposits formed on hot air test rig [21], diesel-run and biodiesel-run are compared in Fig.7 (a, b, c). By physical observation, the deposits in hot air resemble pure urea concerning color and physical nature. The deposits of diesel-run colored pale yellow. The deposits of biodiesel exhaust are reddish, resembling the color of biodiesel used. Deposits of urea in hot air conditions were structurally segregated with uniformity along the direction of exhaust gas flow (Fig.7 a). However, this kind of uniformity is not found in the other two conditions. The segregation of deposits in the latter two cases formed out of the compaction area and is not found with uniformity. The deposits are structurally different as they are formed at low temperatures in different environments.

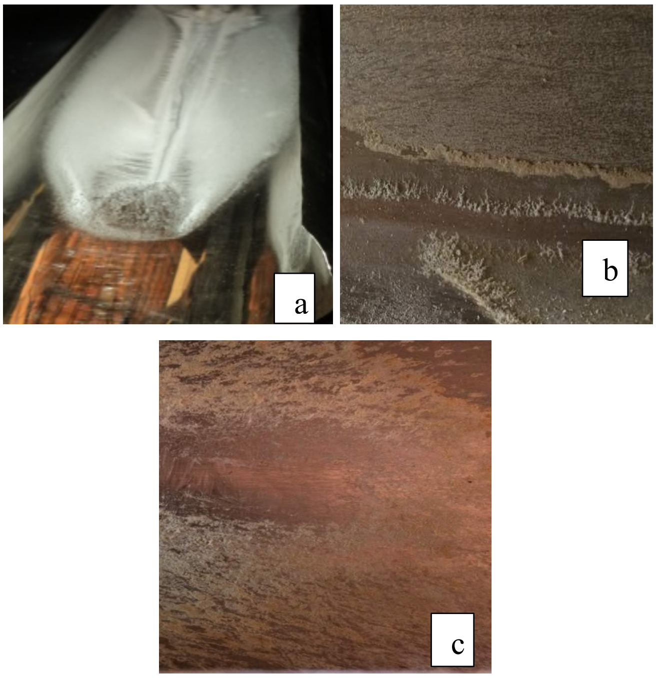


Fig.7. Physical nature of deposits a) pure air [21] b) Diesel c) Biodiesel.

3.2.4 Deposit conversion and Entrainment Characteristics

Incomplete conversion of urea and deposit formation is an undesirable phenomenon. The deposits formed at low temperatures are depleting in nature at elevated temperatures. When engine load increases, the temperature increases and thus a substantial amount of deposits deplete. This scenario is undesirable as it increases NH_3 concentration, leading to NH_3 slip at the catalyst exit. Another phenomenon that is occurring is the entrainment of particles from the surface of UWS film as UWS particles rebound or splash with the support of velocity-driven shear flow. A portion of these entrained droplets enters into section 2 and forms deposits thereon. The next phenomenon is droplets of impaction break into smaller sizes after rebound and droplets are carried away by the exhaust gases as they gain momentum. These droplets are more prone to stick onto the catalyst surface or go along with the outgoing exhaust gases. This is better explained with the help of the factor, unaccounted urea fraction (α), defined as the ratio mass of urea taken away by exhaust gas to injected urea mass (without water). Unaccounted urea is obtained by subtracting deposit mass from injected urea mass. Fig.8 indicates unaccounted urea mass fraction (α) vs. time. During the initial stage of deposition, the evaporation and entrainment are larger due to impaction over the metal wall, which is at a high temperature. As time progresses, the deposits continue to grow without depletion as the temperature is less than the melting temperature of urea. At higher temperatures, moisture supports urea depletion [19], but it supports the formation of deposits at lower temperatures. Additionally, the top layer of the deposits catches up a fresh layer of UWS and leads to faster growth of deposit sublayers if exhaust temperature is low. This phenomenon is clearly observed by the decrease of cumulative unaccounted urea fraction as time progresses.

Urea decomposes at 133°C. As the operating temperature is less than 133^{0}C, deposits formed are of pure urea. Fig. 8 shows the variation of unaccounted urea mass fraction vs. time for two different flow rates when the engine runs on diesel. This depicts unaccounted urea increasing with flow rate. For both the flow rates, the α remained the same for the initial 3 minutes and started differing thereafter for up to 10 minutes. At an exhaust temperature of 90°C, urea is taken away by the exhaust gases rather than conversion. It is also noted that for the time of 10 minutes, it is found that deposit mass is more than the actual mass of urea, indicating incomplete evaporation. This situation may arise in extremely cold weather conditions when the dosage is over-stoichiometric and remnant urea has water even at higher operating temperatures.

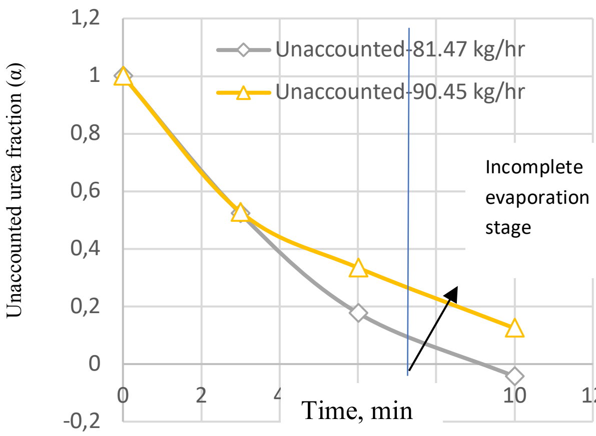


Fig.8. Unaccounted urea fraction vs. time for 407 engines at no load and full load conditions running with diesel.

Referring to Fig.9, the unaccounted urea fraction is comparatively higher for the case of biodiesel run. This gives the inference that urea is taken away by biodiesel exhaust representing increased entrainment characteristics. So, even though the deposits are lesser in the impaction area, there are high chances of urea being taken by the exhaust gases and depositing over the catalyst. For the initial 3 minutes, the same trend decreasing is seen for both the cases of diesel and biodiesel exhausts. It is noteworthy that for higher flow rates, unaccounted urea fraction is increasing after 3 minutes showing the marginal effect of flow rate in reducing deposits and increase in unaccounted mass.

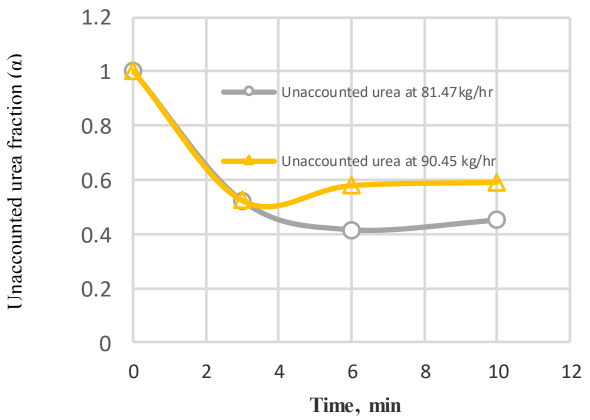


Fig.9. Unaccounted urea fraction vs. time for 407 engines run at no load and full load conditions with biodiesel.

When unaccounted urea mass is found varying, concerning flow rates it is clearly understood that deposit formation is inversely proportional to flow rate and temperature. Higher the mass flow rate of exhaust gas, the greater the ability to carry UWS droplets in the exhaust line, thereby entrainment increases. At lower temperatures, the entrainment is higher during the initial stages leading to lesser deposits. As deposits increase, the tendency of evaporation decreases, and UWS injected spreads over the existing layer, and deposits start growing. This results in a decrease in unaccounted urea fraction as time progresses. This phenomenon is more pronounced at a low-temperature range of less than 130°C. A similar trend is observed for two different flow rates for the engine running with both diesel and biodiesel of 10% blend with a slight decrease in deposits for the latter case. Further, from an entrainment viewpoint, the flow rate has a considerable effect due to significant changes in the momentum of the droplets in the case of biodiesel run conditions.

The non-renewable fossil fuels in automobiles create pollution to the environment [28]. The problem of an automobile diesel engine is the emission of NO_x which can be eliminated by SCR techniques. In many countries, Electric Vehicles (EVs) are encouraged to control air pollution [29]. However, Electric vehicles (EVs) which produce zero emissions destabilize the power systems during peak hours due to excess power requirements as the number of EVs increases in the years to come [30]. There is a significant impact of EVs on the entire value chain of the electric industry, which contain power generation, power grid and consumer facilities [31]. Plug-in Hybrid Electric Vehicle (PHEV) seems to be sustainable towards air pollution, but on the other hand, the production cost of hydrogen is high [32]. SCR system will be a reliable aftertreatment technique for diesel engines even with the advent of Electric Vehicles.

4. Conclusion

Deposit formation is an undesirable phenomenon in the Urea-SCR system and requires the development of mitigation methods. Before it, factors affecting deposit formation are well understood. Biodiesel being alternative to fossil fuels is used as biodiesel with up to 10% blend with diesel. SCR on diesel/biodiesel run engines running at low-temperature face a lot of challenges. A parametric study was done on diesel-run engines, and it is extended for biodiesel to compare the variation in deposit formation at low temperatures. The study is limited to a short duration, the equivalent of a longer duration is obtained by stoichiometric dosage. The dosage of UWS was increased to get the equivalent of a longer duration. Following conclusions were drawn from the study.

Temperature and flow rate have substantial effects on deposit formation characteristics and it has an inverse relationship between both of them. Additionally, it infers that deposit formation is reduced due to increased turbulence.

Comparatively, the deposit formation of urea is less for biodiesel exhaust than diesel exhaust due to the high NO_x content in biodiesel and also due to differential wetting and entrainment characteristics of biodiesel.

The physical nature of deposits for the deposits formed in air, diesel, and biodiesel are different, and it is essential to know their characteristics from a growth perspective.

The fuel nature has a detrimental effect on the deposit formation as we noticed deposits of urea are lesser for biodiesel exhaust than diesel exhaust due to higher NO_x content in biodiesel exhaust and also due to wetting and sticking characteristics of biodiesel over metallic surfaces.

Acknowledgments

The authors would like to thank the Department of Mechanical and Industrial Engineering, Manipal Institute of Technology, and Manipal Academy of Higher Education for writing this paper.

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