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Conversion Efficiencies of Urea –SCR System for Mahua Methyl Ester Fuelled DI Diesel Engine

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Abstract: Stringent emission regulations on diesel-powered vehicles and some of biodiesel emissions have led to development of new technologies to reduce emission of nitrogen oxides (NO_X). Out of the choices available, Selective Catalytic Reduction (SCR) has shown to be the most promising exhaust after-treatment system for reducing oxides of nitrogen in the near term in-use applications. SCRs use the ammonia containing compound urea, as a reducing agent. This paper describes an experimental investigation of Urea-SCR,which has been designed for comparing efficiency of the SCR system for diesel and biodiesel. For this study, a SCR exhaust system was tested on a steady state, direct injection Kirloskar single cylinder diesel engine. Mahua Methyl Ester (MME) oil has used as a biodiesel. From the experimentation, it was concluded that the conversion efficiencies were higher for diesel comparable to biodiesel. The analysis also shows the Urea SCR system has a maximum of 93.4% NO_X conversion efficiency of diesel fuel. For biodiesel, maximum NO_X conversion efficiency of Urea-SCR was approximately 49%. This experimentation also revealed that the Urea-SCR system hasan excellent HC conversion efficiency at all engine loads and using both fuels.

Key words: Selective Catalytic Reduction System · DI Engine · Mahua Oil · Biodiesel · CO_2 · NO_X

INTRODUCTION

Diesel engine is an internal combustion engine, uses compression to ignite the hydrocarbon fuel (i.e. Diesel) to start the combustion and to convert the chemical energy into useful work. Therefore, environmental concerns attributable to polluting gases, i.e. oxides of nitrogen (NO_X), oxides of carbon (CO and CO_2) and unburnt hydrocarbon (HC) are associated with the use of diesel engines. However, diesel engine offers higher thermal efficiency and durability in comparison with a petrol engine that makes it as a better choice for many applications; automobiles, particularly in heavy-duty vehicles, locomotives, ships, farm machinery, generators for backup power, etc. Despite their advantages over petrol engines, diesel engines has specific concerns relates to soot, smoke and particulate matter released by diesel fuel. Thus, investigations have been underway to explore the role of diesel derived from renewable sources into diesel engines. Diesel derived from different vegetable oils, oil from bio-waste, algae, etc., is being tested in diesel engines by many researchers. In fact, Rudolph diesel who invented the diesel engine tested the engine using peanut oil over 100 years ago and its use continued within the agricultural community as fuel for tractors, pumping water and other agricultural machinery.

Vegetable oils are triglycerides (glycerin esters) of fatty acids. Alcohol esters of fatty acids prepared by the transesterfication of the glycerides, wherein linear, mono-hydroxyl alcohols react with vegetable oils in the presence of a catalyst to produce alcohol esters of vegetable oils and glycerin as a by-product. This transesterfication reaction is affected by the molar ratio of glycerides of alcohol, catalyst used, reaction temperature, reaction time and free fatty acids and water content of oils or fats [1].

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As an alternate fuel, vegetable oil is renewable and contains lesser sulfur to petroleum diesel. The combustion of vegetable oil produces negligible sulfur dioxide emissions and much lesser toxic emissions. In principle, vegetable oils are carbon neutral because the carbon dioxide (CO_2) released by combustion is absorbed back for photosynthesis by the plant source. Vegetable oil is biodegradable, safe to store and transport and does not cause other environmental or health problems. Several vegetable oils are of edible, such as rapeseed oil, sunflower oil, cottonseed oil, palm oil, olive oil etc. that have resulted in fuel versus food debate. In addition, various non-edible oils such as Jatropha, Mahua, Karanja oils that are available potentially used as alternate fuels for diesel engines. However, the choice mainly depends upon the climate and soil conditions and availability, thus different nations are looking into different vegetable oils for diesel fuels. For example, soybean oil in the United States, rapeseed and sunflower oils in Europe, palm oil in the Southeast Asia (mainly Malaysia and Indonesia) and coconut oil in Philippines are being believed possible substitutes for diesel fuel [2].

This paper presents experimental results of performance of Mahua Methyl Ester (MME) in a diesel engine, obtained from the two species of the genus Madhucaindica and MadhucaLongifoliafound in India. The aim of the research was to investigate the performance of MME in the engine and to investigate the emissions. For this Mahua oil wastransesterifiedwith Methanol in the presence of Sodium Hydroxide (NaOH) catalyst as per the standards established for maximum yield of biodiesel. Different after-treatment techniques for control exhaust emissions searched. Selective catalyst reduction (SCR) is a commonly used in lean burn engines for reducingNO_xemissions. The experiments are also being conducted to study the performance of the SCR with MME.

Background Literature

Mahua Oil: The two species Madhucaindica and Madhucalongifolia are closely related and no distinction is available in the trade of their seed or oil. The drying and de-cortification yield 70% kernel on the weight of seed. The kernel of seed contains about 50% oil. The oil yield in an expeller is nearly 34-37%. The fresh oil from properly stored seed is yellow in color. The properties of Mahua oil and of MME are as shown in Table 1. MME oil has a lower calorific value but higher density, indicating that the calorific value of MME oil on a volumetric basis approaches the volumetric calorific value of diesel fuel. The Mahua oil Cetane number increases with flash and fire point [3-5].

Table 1: Properties of Mahua oil [5][4]

Properties	Diesel	Mahua oil	MME
Kinematic viscosity at 40°C (CST)	3.05	39.45	5.8
Density (kg/m^3)	850	924	916
Flash point (°C)	56	230	129
Fire point (°C)	63	246	141
Net calorific value (KJ/kg)	42800	37614	39400

Many researchers have tested the use of Mahua oil in diesel engines. Sukumar Puhan *et al*. [6] conducted experiments on performance and emission study of MahuaOil Ethyl Ester with the some modification of pressure and injection timing of the fuel injection. It is concluded reductions of Carbon monoxide (CO), Hydrocarbons (HC) and oxides of nitrogen to nearly 58, 63 and 12%, respectively. Similarly, Raheman and Ghadge [7, 8] conducted experiments to study the performance of Mahua for various blend ratios, various compression ratios and ignition timing. It is reported that similar performance, efficiency could also be achieved on par with Diesel by B100 (pure biodiesel) with increased compression ratio and advancing injection from 30 to 40° before the top dead center (TDC) of the engine.

Catalytic Converters: Reduction in NOx emissions from compression-ignition engines has previously been addressed by the addition of exhaust gas to incoming air charge, known as exhaust gas recirculation (EGR). Recently, the two techniques suggested for the reduction ofNOx emissions under lean exhaust conditions - Selective Catalytic Reduction (SCR) and the lean NOx trap or NOxadsorber. Instead of precious metal-containing NOx adsorbers, manufacturers almost selected base-metal SCR systems that use a reagent such as ammonia (AdBlue) to reduce the NO_X into nitrogen. Ammonia supplied to the catalyst by the injection of urea and water into the exhaust pipe, which then undergoes thermal decomposition and hydrolysis into Ammonia.

Oxidation catalytic converter owes to the oxidation of some of the contents of exhaust fumes, in particular carbon monoxide and un-burnt hydrocarbons. Generally, used in diesel engines because of the exhaust gases contain a large quantity of oxygen generated by lean-burn combustion. This catalytic converter however, does not allow the treatment of NOx gases and soot usually present in diesel exhaust fumes. It may therefore

Table 2: Status of Emission Control Devices Research, Development and Demonstration [8, 7]

Emission Control Device	Description	Typical / Expected No_x Efficiency	Typical / Expected PM Efficiency	Status
NOxAdsorber	Adsorbs NO and oxygen during lean operation, uses CO and HC from periodic rich operation to convert to N_2	>80%	30%	In development: available in 2007
Diesel Particulate Filter	Collects particles in diesel exhaust	None	80 to 90%	Verified for some heavy duty engines model year and duty cycles in CA
Oxidation Catalyst	Oxidizes HC and CO in exhaust	None	20 to 30%	In commercial use in bus engines; not verified for non-bus heavy-duty vehicles
Selective Catalytic Reduction Catalyst	Converts NOxto N_2 and O_2 in presence of ammonia, or ammonia carrying agent (e.g., urea)	>80%	30%	In development/ demonstration; Available 2005 – 2007. Requires reductant dispensing and storing infrastructure
Non-thermal plasma	High energy electrons convert exhaust Pollutants to inert species	>65%	30%	In demonstration phase for light – duty only; in development for heavy-duty applications

necessary to associate the oxidation catalytic converter to catalytic reduction kind and if required, a particulate filter to guarantee an efficient and more thorough treatment and meet regulations in force.

Selective Catalytic Reduction (SCR) is a promising technology with the potential to achieve large NO_X and some PM reductions. SCR has been used to control stationary source NO_X emissions for over twenty years. It is at present demonstrated in mobile diesel applications, both in Europe and in the United States [9, 10]. Table 2 describes the status of Research, Development and Demonstration of emission control devices.

SCR used in lean-burn combustion engine typically, diesel engine to reduce NO_X. For compression-ignition (i.e., diesel engines), the more commonly used catalytic converter is the Diesel Oxidation Catalyst (DOC).

This catalyst uses O_2 (oxygen) in the exhaust gas stream to convert CO to CO_2 and HC (hydrocarbons) to H_2O (water) and CO_2. These converters often operate virtually at 90% efficiency; eliminating diesel odor and helping to reduce visible particulates (soot). These catalysts are not active in NO_X reduction because any reduce presents should react first with the high concentration of O_2 in diesel exhaust gas.

The LEV II and EURO V legislation in 2007/2008 require a highconversion level of nitrogen oxides to meet the emission levels for diesel Sport Utility Vehicles (SUVs) and trucks. Almost all the light–duty diesel vehicles of US and European trucks have the catalytic systems to meet the new federal emissions regulation since 2010[11]. Another example of successful implementation of SCR to meet the emissions requirements in 50 states in the US is for Passat's 2.0-liter TDI Clean Diesel in-line four-cylinder engine [12, 20].

Researchers are also conducting experiments on the SCR using the biodiesel and biodiesel blends. A reduction of $NO_X$of 73% was achieved with Soybean biodiesel when ethanol –SCR application on Ag/Al_2O_3 catalyst [13]. However, to reduce the total hydrocarbons (THC) and CO the set-up had modified with two catalytic systems with a small increase in NO_Xemissions. Similarly, SCR with urea as a reducing agent was also beinginvestigated for many years and today is the well-establishedtechnique for stationary diesel engines. The addition of external injection of a reducing agent (urea or ammonia) breaks up the NO_X into nitrogen and water.

Studies on road emissions of buses with urea - SCR and EGR + DPF using diesel and biodiesel reveals better performance with urea – SCR than EGR + DPF [13-15]. The degree of EGR is greater and during rapid accelerations, the degree of EGR is less, with a weaker control of NOx. In this sense, the SCR + Urea performs better than EGR + DPF. Additionally, reported that as the biodiesel mix increases, NOx also increases owing to the presence of an increase in oxygen content. However, unburned hydrocarbon (HC) and the particulate matter (PM) levels are remained low and no significant differences observed for the B20 and B100 in comparison to the reference diesel fuel [11, 15, 16].

It is one of the most promising ways to reduce NO_X emissions from diesel engines. Several studies have reported that urea-SCR systems affect more when coupled with an oxidation catalyst upstream to convert some of the NO to NO_2. This promotes NOx reduction through the fast-SCR reaction path on the SCR catalyst [11, 15,17-19].

A urea-SCR plays a significant role not only in the abatement of NOx but also results in the improvement of the performance enhancement of the engine.

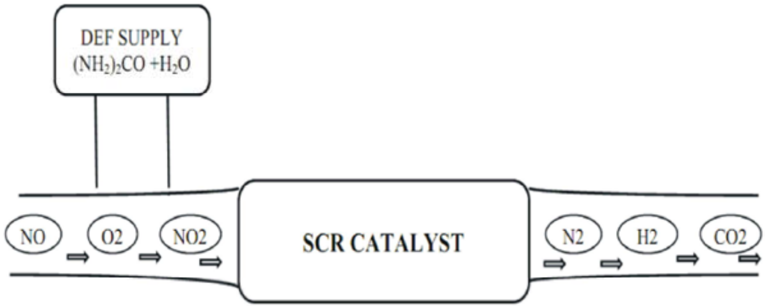


Fig. 1: Principle of SCR

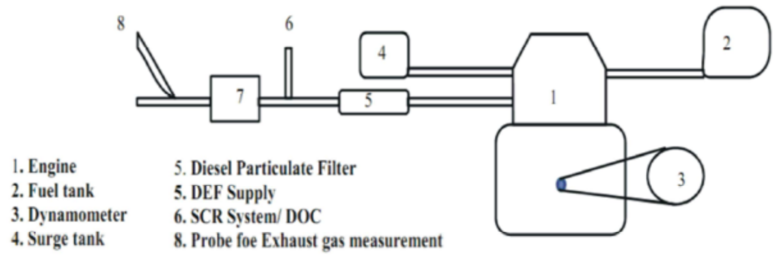


Fig. 2: Experimental Set-up

These advantages include increased fuel economy, efficient power and torque production over a long life, Enhanced durability and reliability resulting in longer service intervals and optimized power potential of the engine.

The compact urea-SCR can reduce NOx pollutants by over 70% of the European transient cycle (ETC) and European steady-statecycle(ESC)[15, 20]. Miller*etal*.[16] have reported on the cold US transient cycle that the reductions of NOx and PM with a urea-SCR catalyst are 55.6 and 22.2%, respectively. While reduction of NOx and PM on the hot US transient cycle are 70.5 and 25%, respectively. Heavy-duty trucks alone, SCR can reduce NO_X emissions up to 90%, hydrocarbons and carbon monoxide by 50-90% and PM emissions by 30-50% with reliable and proven capabilities. Figure 1 shows the principle of the SCR system with the components. There are 3 main components of the SCR system;

- Diesel exhaust fluid (DEF)
- A solution of urea and purified water
- Hot exhaust and catalytic converter

Diesel Exhaust Fluid (DEF) is a crucial component of SCR technology. It is a 32.5% strength urea- 67.5% water solution. It is non-toxic, non-polluting and non-flammable with an odor similar to that of ammonia. DEF is nonetheless safe to handle and store, posing no serious risk to humans, animals, equipment or the environment with proper handling. DEF will begin to freeze to a slushy consistency at – 11°C. SCR designed to heat the DEF storage tank, providing lines that reduce the melting time. If DEF freezes when the vehicle was shut down, ignition and normal operation of the vehicle will not be inhibited, the SCR heating system quickly returns the DEF to liquid form without upsetting the vehicle's operation even if the vehicle is operated in such a way that is runs out of DEF, the vehicle will not shut down. However, additional methods (yet to be determined) are to be encouraged to enable the operator to refill the DEF tank. Depending on vehicle operation, DEF consumption is approximately 2 to 4% of fuel consumption. Therefore, the tank must sized according to usage requirements and generally allowing 2-3 fuel refills before needed to replenish the DEF tank.

In the following sections, we present the results of an experimental study of testing the Urea-SCR uses Mahua Methyl Ester oil with the objectives of studying the combined performance of the SCR and MME.

Experimental Set-up: A Kirloskar 5 HP single cylinder DI engine has used for the experiment. Fig. 2 shows the experimental setup with SCR, Diesel Particulate Filter (DPF) and the dosing location. Tables 3 and 4 respectively show specifications of the engine used and the dosing details of DEF as specified by the supplier.

For benchmarking, the experiment had conducted first with diesel as a fuel and without the attachment of the catalytic converter. Subsequently, the experiments being conducted using a catalytic converter and a catalytic converter with SCR using diesel then followed by Mahua Methyl Ester fuel. Measurements of Fuel consumption of the both fuels usage and exhaust

Table 3: Dosing Module Specifications

Dosing quantity	2.4 liter/min.
Dosing pressure	1.8 bars
Atomization	≤ 400 µm
Operating voltage	12 V
Injection line between supply module & dosing Module	3805 mm

Table 4: Specifications of Kirloskar Engine

Make	Kirloskar AVI
Bore	80 mm
Stroke	110 mm
Number of cylinders	1
Compression ratio	16.5
Engine speed	1500 RPM
Power	5 HP/3.7 W
Cooling system	Water cooled

emissions with the scheme of attachments discussed above recorded in each case once the engine comes to steady condition. For the consistency of measurements at every load the average of three trials are considered.

A D.C. Shunt dynamometer is used for the loading the engine and the experiment was restricted to 80% full load only with an apprehension of engine failure. For the exhaust gas measurements NETEL make of MGA – II is used.

RESULTS AND DISCUSSION

Figs. 3 and 4 show the performance curves of the engine. As seen from these figures the Specific Fuel Consumption (SFC) of Mahua Methyl Ester (MME) was higher than diesel at 20, 40 and 60% of full load. However, SFC at 80% of full load for MME is lower than that for diesel. This is because of the high density of MME, results in good performance and low fuel consumption of MME at high loads.

The brake thermal efficiency (BTE) of MME was higher than that of diesel fuel (Fig. 4). A value of higher than 21.8% was observed with MME at 80% of full load.

The exhaust gas emissions either with or without after-treatment attachments and the conversion efficiencies of the attachments at different loads are shown in Figs. 5 to 8.

CO Emissions: Figs. 5a and 5b show the CO concentration variation at various loads on the engine. The CO concentration is higher with the MME fuel in comparison to diesel at no loads and 20% of full load and it is less in comparison with diesel at other loads including 80% of full load [6, 20]. Nearly a reduction of 28.4% at 80% of full load was observed.

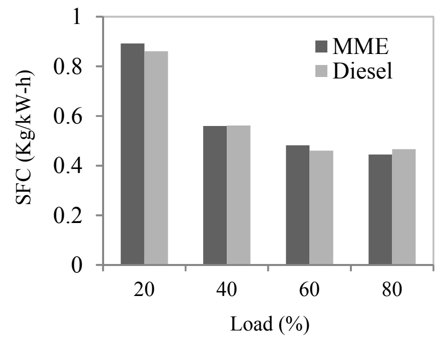


Fig. 3: Variation of SFC with load

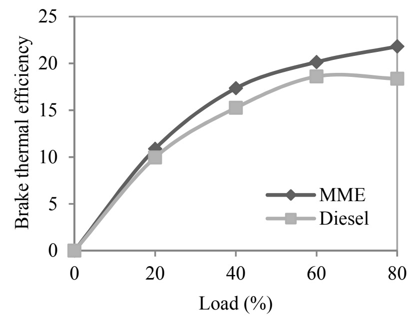
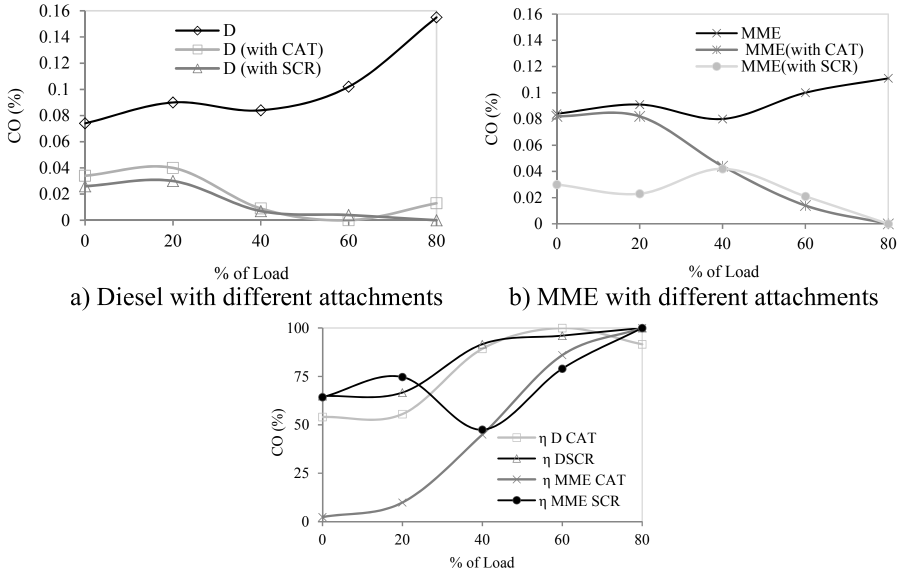


Fig. 4: Variation of $\eta_{thermal}$ with load

With the attachment of a catalytic converter (CAT) alone, the CO of MME is relatively higher than the CO of diesel initially and it is approaching diesel for the higher loads. The average conversion efficiency of CAT is 78.1% and with the addition of SCR 83.85% of CO observed in diesel fuel operation (Fig. 5c). That means it gives an act of possible oxidation in SCR too in the diesel operation.

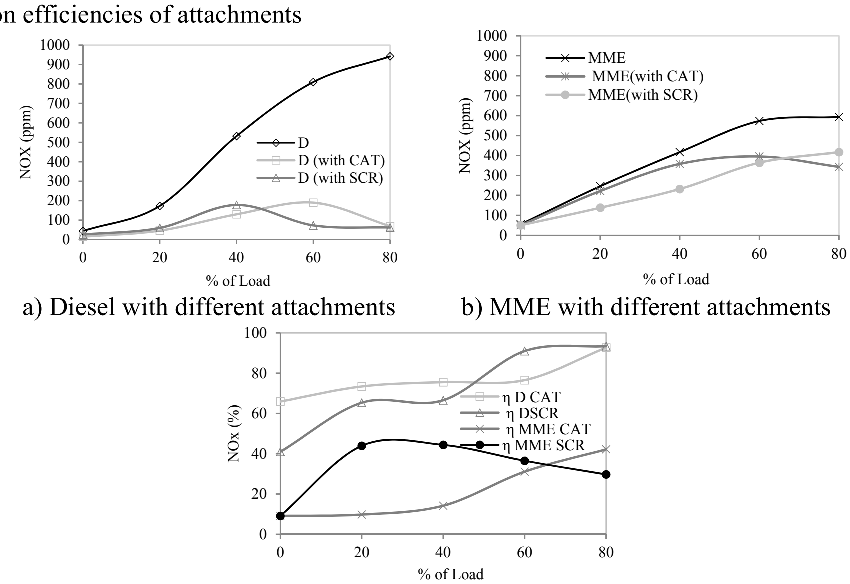
Fig. 5c Shows the conversion efficiencies of the attachments when intended for the after-treatment of exhaust gases. The conversion efficiency of oxidation of CO with diesel is superior to that of Mahua Methyl Ester. The average conversion efficiencies of 48.7% with CAT and 73% with the addition of SCR are achieved at MME operation. The reasons for the improvement in the conversion efficiency with SCR attachment is further oxidation and the self-oxygen content present in the fuel.

Oxides of Nitrogen (Nox): TheNOx emissions from diesel is more that of the MME nearly 349 PPM more at 80% full load as it is shown in Figs. 6a and 6b[6]. This is because of the average temperature of combustion prevailed. This is also one of the reasons for the declined efficiency for the after-treatment attachments of MME as a fuel (Fig. 6c). The average efficiencies for diesel with CAT alone, with the addition of SCR and MME with CAT, with addition SCR are 87.6, 71.5, 21.2 and 33.7%, respectively.



a) Diesel with different attachments
b) MME with different attachments
c) Conversion efficiencies of CAT and SCR with Diesel and MME

Fig. 5: Variation of CO with the load when fuelled with diesel and MME with and without attachments and the conversion efficiencies of attachments

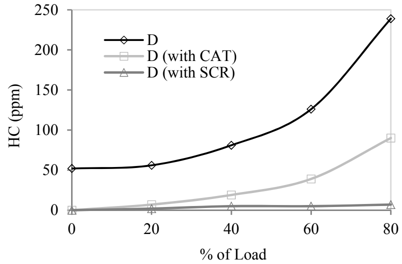


a) Diesel with different attachments
b) MME with different attachments
c) Conversion efficiencies of CAT and SCR with Diesel and MME

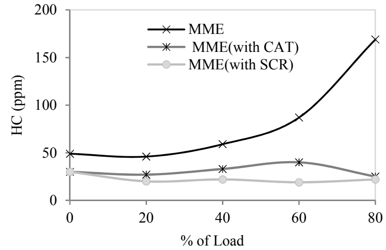
Fig. 6: Variation of NO_x with the load when fuelled with diesel and MME with and without attachments and the conversion efficiencies of attachments

Unburned Hydrocarbon (HC): Though, the HC emissions are relatively high with diesel the conversion efficiencies of the attachments did effectively in bringing down the HC (Figs. 7a to 7c). Originally, with MME and without attachments the HC emissions are lesser than diesel [6, 5]. The conversion efficiency of either with diesel or MME with the either CAT alone or CAT with SCR is above 60% at 80% full load operation [14].

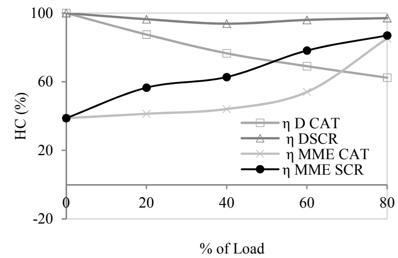
Carbon Dioxide (CO_2): CO_2 emissions are almost same for diesel and diesel with SCR at near full load operations (Figs. 8a, 8b). There is a maximum of 2.3% difference of CO_2 emissions between diesel and MME at near full load operation and without any attachments. Fig. 8c reveals maximum oxidation of CO to CO_2 is taking place in the catalytic converter. The maximum conversion efficiencies of CO_2 observed with CAT alone and addition of SCR in diesel fuel operation were 54.8 and 19.6%, respectively.



a) Diesel with different attachments

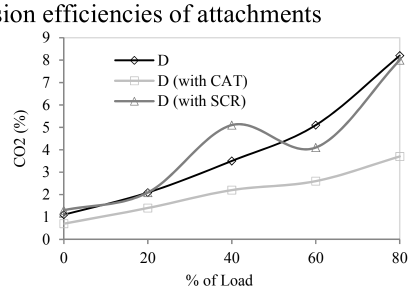


b) MME with different attachments

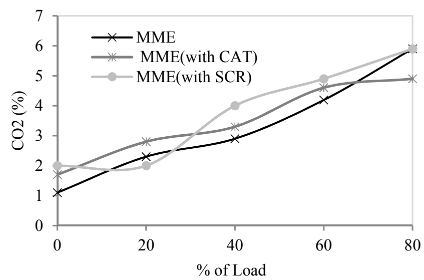


c) Conversion efficiencies of CAT and SCR with Diesel and MME

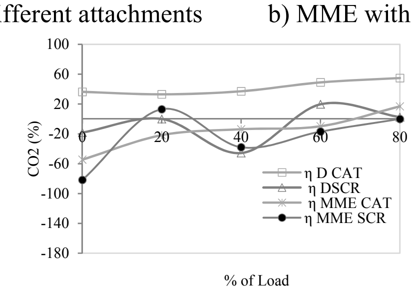
Fig. 7: Variation of HC with the load when fuelled with diesel and MME with and without attachments and the conversion efficiencies of attachments



a) Diesel with different attachments



b) MME with different attachments



c) Conversion efficiencies of CAT and SCR with Diesel and MME

Fig. 8: Variation of CO_2 with the load when fuelled with diesel and MME with and without attachments and the conversion efficiencies of attachments

CONCLUSIONS

The study demonstrated the use of MME for the SCR designed for diesel engine operation. It is observed that the SCR performing well during diesel operations. Following are the conclusions made.

- MME consists of oxygen also as an element in its composition. Therefore, much reduced CO emissions and less HC emissions observed. Furthermore, it also attributed for the complete combustion of MME.
- The average surface temperature is lower in case of MME fuel burn. Therefore, less NO_X emissions recorded.
- The efficiency of CAT and SCR depends on the temperature of the operation. Hence, there is declining in the conversion efficiency of the after treatment attachments with the MME fuel operation.

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Abbreviations, Acronyms, Notatiuons/Legends:

B20	:	20% biodiesel + 80% diesel
B100	:	Pure biodiesel
BTE	:	Brake Thermal Efficiency
CAT	:	Catalytic Converter
CO	:	Carbon monoxide
CO_2	:	Carbon dioxide
D	:	Diesel fuel
D (with CAT)	:	Diesel with Catalytic Converter
D (with SCR)	:	Diesel with Selective Catalytic Reduction system
DEF	:	Diesel Exhaust Fluid
DI	:	Direct Injection
DOC	:	Diesel Oxidation Catalyst
DPF	:	Diesel Particulate Filter
EGR	:	Exhaust Gas Recirculation
ESC	:	European Steady state Cycle
ETC	:	European Transient Cycle
HC	:	Hydrocarbons
LEV	:	Low Emission Vehicle
MME	:	Mahua Methyl Ester
MME (with CAT)	:	Mahua Methyl Ester with Catalytic Converter
MME (with SCR)	:	Mahua Methyl Ester with Selective Catalytic Reduction system
NAOH	:	Sodium Hydroxide
NO	:	Nitric oxide
NO_2	:	Nitrogen dioxide
NO_x	:	Oxides of Nitrogen
PM	:	Particulate Matter
ppm	:	Parts per million
O_2	:	Oxygen
SCR	:	Selective Catalytic Reduction
sfc	:	Specific fuel consumption
SUV	:	Sports Utility Vehicle
TDI	:	Turbocharged Direct Injection
η D CAT	:	Conversion efficiency of diesel with Catalytic Converter
η DSCR	:	Conversion efficiency of diesel with Selective Catalytic Reduction system
η MME CAT	:	Conversion efficiency of Mahua Methyl Ester with Catalytic Converter
η MME SCR	:	Conversion efficiency of Mahua Methyl Ester with Selective Catalytic Reduction system

Persian Abstract

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چکیده

قوانین سختگیرانه برای کاهش انتشار اکسیدهای نیتروژن (NO_X) منتشره از وسایل نقلیه دیزلی و همچنین تولید گازهای گلخانه ای بیودیزل منجر به توسعه فن آوری های جدید شده است. برای کاهش اکسیدهای نیتروژن استفاده از کاتالیست کاهشی (SCR) در مجرای گازهای خروجی (وسایل نقلیه) ، در برنامه های کوتاه مدت قابل استفاده می باشد. SCRs، ترکیبی از آمونیاک حاوی اوره را به عنوان یک عامل کاهنده استفاده می کند. در این مقاله یک تحقیق تجربی با استفاده از ترکیب اوره-SCR، برای مقایسه کارایی SCR بین سیستم دیزل و بیودیزل طراحی شده است. برای این مطالعه، از یک سیستم اگزوز SCR در حالت پایدار استفاده شده، که با تزریق مستقیم Kirloskar در موتور دیزل تک سیلندر مورد آزمایش قرار گرفته است. از روغن Mahua متیل استر (MME) به عنوان بیودیزل استفاده شده است. آزمایش ها، نشان داد که بازده تبدیل در سیستم دیزل در مقایسه با بیودیزل بالاتر بود. همچنین تحلیل دادها نشان می دهد که سیستم اوره-SCR ، حداکثر راندمان تبدیل ۹۳.۴٪ NO_X را در سوخت دیزل دارد. برای سیستم بیودیزل، حداکثر بازده تبدیل NO_X با استفاده از اوره-SCR حدود ۴۹٪ بوده است. این آزمایش همچنین نشان داد که سیستم اوره-SCR دارای راندمان تبدیل HC بسیار عالی در تمام بارهای موتور و با استفاده از هر دو نوع سوخت می باشد.