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EMISSION REDUCTION OF METHANOL GASOLINE BLENDED FUELS IN LEAN BURN SI ENGINE USING ZEOLITE-BASED CATALYTIC CONVERTOR

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ABSTRACT

Because of the high thermal efficiency and low fuel consumption, the Gasoline Direct Injection (GDI) engines are preferred by the Automobile manufacturers. Researchers worldwide are focussing to reduce our reliance upon fossil fuel based products and for a cleaner energy environment through the alternative source of fuel. As it is not possible to replace the fossil fuel, we can reduce the usage of biofuels by blending of the gasoline with methanol. Methanol addition in the GDI engine will increase the overall oxygen availability inside the combustion chamber and thus improving the combustion process. As the temperature is increased the formation of the NO_x emission will also increase from the engine. In order to reduce the excess NO_x emissions, a specially fabricated metal doped zeolite based catalytic convertor has been used. The GDI engine was tested for different blends of methanol-gasoline namely M0 (methanol 0% and gasoline 100%), M5 (methanol 5% and gasoline 95%) and M10 (methanol 10% and gasoline 90%) fitted with commercial catalytic convertor and the zeolite based catalytic convertor for the various speeds of the engine rpm (2000, 2200, 2400, 2600 and 2800). The performance characteristics of different methanol-gasoline blends were analysed and the emission reducing capacity of commercial as well asCu-ZSM5 coated catalytic convertor were analysed for all the blends. From the results it can be concluded that the M10 blend is having better brake thermal efficiency (BTE) and lesser unburned HC and CO emissions.

KEY WORDS : Cu-ZSM5 Zeolite, GDI engine, ZSM5, SI engine, NOx reduction, Methanol-gasoline blend.

INTRODUCTION

The crude oil demand is keep on increasing especially in the countries like china and India which are the major consumers of crude oil to meet its energy requirements (Sadala *et al*., 2019). Most of the crude oil energy in the world were spend for the powering the transport and Industrial sectors. This crude oil based Internal Combustion (IC) engines produces various harmful emissions in the environment (Elavarasan, 2019). The major emissions from the IC engines are Hydrocarbons (HC), Carbon Monoxide (CO) and Nitrogen Oxides (NO_X) (Rajasekar *et al*., 2010). To overcome these oil depletion, some countries shifting towards alternative source of energy. Methanol is also a prominent source of the alternative fuel which can be blended with the petrol and can be used in Spark Ignition (SI) Engine (Kumar and Tomar, 2019). This blended methanol fuel requires no modification for lower volumetric composition (Mourad and Mahmoud, 2019). The presence of methanol in the gasoline will increase the anti-knock properties and the brake thermal efficiency of the fuel (Wang *et al*., 2019). Also the presence of the methanol will increase the oxygen content of the fuel and thus reducing the HC and CO emissions (Yang *et al*., 2019b). Zhang *et al*. (2019) have observed that, if the alcohol blend was increased, then the compression ratio of the engine also should be increased in proportion to the blend in gasoline (Zhang and Sarathy, 2016). Zaharin *et al*. (2018), have also confirmed that the testing of the iso-butanol additive in the alcohol blend will not require any modification of the SI engine (Zaharin *et al*., 2018). Thakur *et al*. (2018) have recorded that the maximum brake thermal efficiency were recorded when the 20% of alcohol-gasoline blend was used for testing (Thakur *et al*., 2017). Iodice *et al*., (2018) have found that ethanol-gasoline blends of 20% can overcome the cold starting problem of an SI engine (Iodice, Langella and Amoresano, 2018). Even for 20% of the ethanol-gasoline blends, there is no modification required in the engine (Fan *et al*., 2019). But the increase in the concentration of methanol in gasoline will increase the emissions and also the results in the uneven combustion inside the engine (Biswal *et al*., 2019). In this research we have used various methanol-gasoline blends in a lean burn SI engine and the emission results were tested in commercially available catalytic convertor and a metal doped zeolite based catalytic convertor. The methanol concentration in the gasoline is having good characteristics of converting the unburned HC to H_2O and CO to CO_2, but it will increase the formation of the NO_X. The NO_X formation in the combustion chamber is mainly due to the reaction of the oxygen and the nitrogen at higher temperature. The availability of the oxygen in a lean burn GDI engine is usually more, the addition of methanol content in the mixture will also increase the oxygen availability, this is the reason for the improved combustion process in a methanol blended gasoline fuel (Chang and Park, 2019). Bacariza *et al*. (2019), have already proved that the ZSM5 coated monolith in the exhaust stream have better tendency to reduce NO_X emission (Bacariza *et al*., 2019). The NO_X reduction capacity of the ZSM5 zeolite can be further increased by an added active catalyst metal in it (Balzarotti *et al.,* 2019). Copper, Iron and Cerium were some of the low cost metals that can be used in the ZSM5 zeolite as an active catalyst metal for the reduction of emissions in the exhaust (Ko *et al*., 2019). The results of the NO_X emission reduction can be even increased by adding one more metal in the ZSM5 zeolite coated monolith (Azarikhah *et al.*, 2019). As the ZSM5 zeolite can be obtained from the waste fly ash material from the thermal power station and the catalytic materials were non-precious metal, the cost of the metal doped zeolite catalytic convertor is very much lesser than of the commercial catalytic convertor (Lin *et al.*, 2019). In this study, we have used Cu-ZSM5 type coated monolith for the reduction of the NO_X emissions and the results were compared with the commercial catalytic convertor.

Fuel Preperation

Three types of fuels were considered for testing in the lean burn SI engines. The methanol and gasoline were mixed at three different volume rates were prepared for testing and it was shown in the Table 1 (Godwin *et al*., 2019).

Table 1. Composition of methanol and gasoline used for testing.

S. No.	Sample Name	Volume of Methanol (Vol %)	Volume of gasoline (Vol %)
1	M0	00	100
2	M5	05	95
3	M10	10	90

A. Measurement of Physiochemical Properties

The properties for each fuel blend and the gasoline were presented in the Table 2 (Schifter *et al*., 2011).

Catalyst Preparation

ZSM5 zeolites were bought from and zeolite manufacturing company named zeolyst International from USA and Cupric Chloride was bought from Fisher scientific from India. The ZSM5 zeolite was taken as the base material the $CuCl_2$ was taken as the transition material preparation. The Cu-ZSM5 zeolite was prepared by Na^+ ion exchange method for the coating in the monolith for the NO_X emission reduction.

B. Na^+ ION Exchange Method

Because of its simplicity the Na^+ ion exchange method was considered for the preparation of the Cu-ZSM5 zeolite. The purchased 100 g ZSM5 was taken and added with the 100 mL of 0.5M $CuCl_2$ and the whole solution was poured into a beaker containing 1000 mL distilled water. The solution is allowed to stirred using a magnetic stirrer for about 16 hours in normal room temperature for the ion exchange reaction to takes place between Na and Cu (Yuan *et al*., 2018). Then this mixture is filtered and washed with the distilled water to remove the free ions and it was placed in a furnace at 500 ^oC for 6 hours to get the final product Cu-ZSM5 (Yoldi *et al.*, 2019).

Table 2. Some Properties of gasoline and methanol-gasoline blends

Properties	M0	M5	M10	Methanol
Net Heating Value (MJ/Kg)	42.600	41.462	40.268	19.850
Density (kg/m^3 at 15 ^{o}C)	750.8	751.9	754.1	796
Kinematic Viscosity (mm^2/s at 40 ^{o}C)	0.494	0.529	0.548	0.596
Research Octane Number	95	-	-	108.7
Motor Octane Number	85	-	-	88.6
Latent Heat of Vaporization (kJ/kg)	-380	-	-	1185
Auto Ignition Temperature (^{o}C)	-370	-	-	423
Distillation (%)				
Initial Boiling point	45	64	42	43
30	71	64	58	55
60	113	64	110	108
90	168	65	163	165
End Boiling Point	207	66	207	206
Recovery (%)	96	99.2	96.4	96.4

C. X-ray Fluorescents (XRF)

The chemical components present in the ZSM5 zeolite and the prepared Cu-ZSM5 zeolite was identified by XRF method using Philips Spectrometer PW1401. The results obtained for both the commercial ZSM5 zeolite and the prepared Cu-ZSM5 zeolite were shown in the Table 3. It can be observed from the table that the percentage of sodium oxide was decreased and the percentage of Copper was increased in the Cu-ZSM5 type zeolite. This is because of the ion exchange happened between Cu and Na during the Na^+ ion exchange method.

Table 3. % Mass of Zsm5, Cu-Zsm5

Composition	ZSM5	Cu-ZSM5
SiO_2	88.372	87.012
Al_2O_3	3.256	3.091
Fe_2O_3	0.114	0.110
CaO	0.014	0.014
MgO	1.150	1.050
SO_3	0.134	0.126
Na_2O	7.001	1.515
K_2O	0.00	0.00
CuO	0.00	5.012
P_2O_5	0.00	0.00
TiO2	0.025	0.22
BaO	0.00	0.00
LOi	0.00	0.00

D. Cordierite Monolith

The Oxidation monoliths and some blank monoliths for the coating of Cu-ZSM5 zeolite were purchased from Bo cent Advanced Ceramics Co Ltd, China for the preparation of after treatment device. The monoliths have 400 cpsi and cell density with 0.17 mm wall thickness and the diameter and the length of the monolith were equal size of 90 mm. The exhaust gas was initially allowed to pass through the oxidation monolith and then to the Cu-ZSM5 zeolite. The oxidation monolith can help to convert CO to CO_2 and HC to H_2O and the Cu-ZSM5 coated monolith can help to reduce the NO_X emission to N_2 and O_2. For the preparation of Cu-ZSM5 zeolite coated monoliths. Figure 1 shows the picture of blank monoliths.

Fig. 1. Picture of Blank Monoliths

E. Monolithic Washcoating

Because of the effectiveness and the simplicity of operation, Dip coating method was adapted for the coating of the Cu-ZSM5 zeolite to the monolith. The initial step was the preparation of the slurry having 50% of Cu-ZSM5, 4% of silica gel and remaining 46% of distilled water. The weight of the blank monolith should be identified initially with the help of a weighing machine. The Blank monoliths were made to immerse the slurry completely for 2 minutes. Then the monoliths were blown with the compressed air from one end to other to remove the excess sticky slurry and it was placed in a closed type muffle furnace for about 2 hours at 130 °C. Again the same process from immersing the monolith in the slurry was repeated till the weight of the deposition reaches 16% weight of the monolith. After this, the monolith is Calcined at 500 °C for about 5 hours (Mehla *et al*., 2019).

F. Fabrication of Catalytic Converter

The Oxidation monolith and laboratory made Cu-ZSM5 zeolite coated monolith were placed in a steel casing and then fitted with the exhaust stream of the engine. The photographic view of the Cu-ZSM5 coated catalytic convertor in the engine was shown in the Figure 2 and the commercial catalytic convertor is shown in the Figure 3.

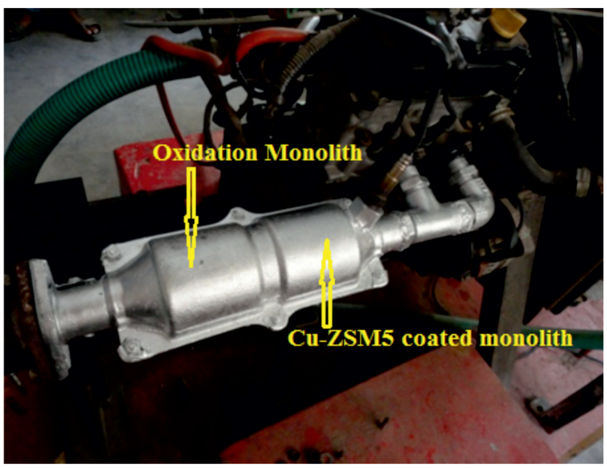

Fig. 2. Picture of Cu-ZSM5 coated catalytic convertor

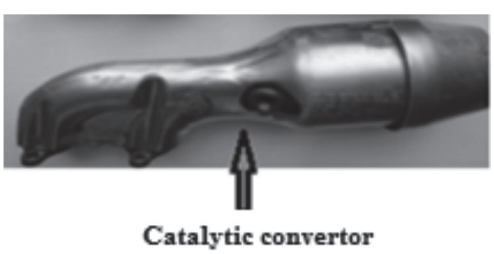

Fig. 3. Picture of Commercial catalytic convertor

Experimental Apparatus and Procedure

The lean burn SI engine was connected with an eddy current dynamometer was used for the conduct of the experiment. The schematic view of the experimental setup is shown in Fig. 4. The experiment procedure consists of testing of the three types of methanol-gasoline (M0, M5, M10) blends in the SI engine at different speed conditions and evaluating the performance and emission characteristics for each blend. The emission values are observed with the help of the AVL 444,a 5 gas analyser. Then the two methanol-gasoline blends (M5, M10) were taken for the testingto evaluate the emission reduction capacity of commercial catalytic convertor and with Cu-ZSM5 coated catalytic convertor. In all the conditions the engine was allowed to reach the steady state and then the emission values are noted in the gas analyser. The general specifications of the test engine are given in Table 4.

Table 4. Specification of Petrol Engine

Type	SI Engine
Number of cylinders	2
Displacement	624 cc
Bore	73.5 mm
Stroke	73.5 mm
Compression Ratio	9.5:1
Fuel	Petrol
Cycle	4-Stroke
Max. Engine output	25.74 kW @ 5250 rpm
Max. Torque	48 Nm @ 3000 rpm
Orifice Diameter	20 mm
Cooling System	Water
Loading Device	Eddy current dynamometer

The experiments are conducted at different engine speeds ranging from 2200 to 3000 rpm by 200rpm increments, and at each of the engine speeds 5 different fuels were tested. The fuel blends were shown in Table 1. The emission generated from these fuels were recorded initially without attaching the catalytic convertor, secondly with OEM catalytic convertor and finally within house made Cu-ZSM5 catalytic convertor. A total of 30 experiments were conducted. Engine brake power exhaust gas temperature, fuel consumption and emissions such as CO, HC, CO_2, O_2 and NO_X were measured during the experiments. For each experiment, the engine was allowed to reach a steady state condition and then the measurements were recorded in a few seconds. No data was taken until brake power and speed were maintained at 1% of the fluctuation.

RESULTS AND DISCUSSION

G. Brake Thermal Efficiency

The variation of the various blends of the methanol-

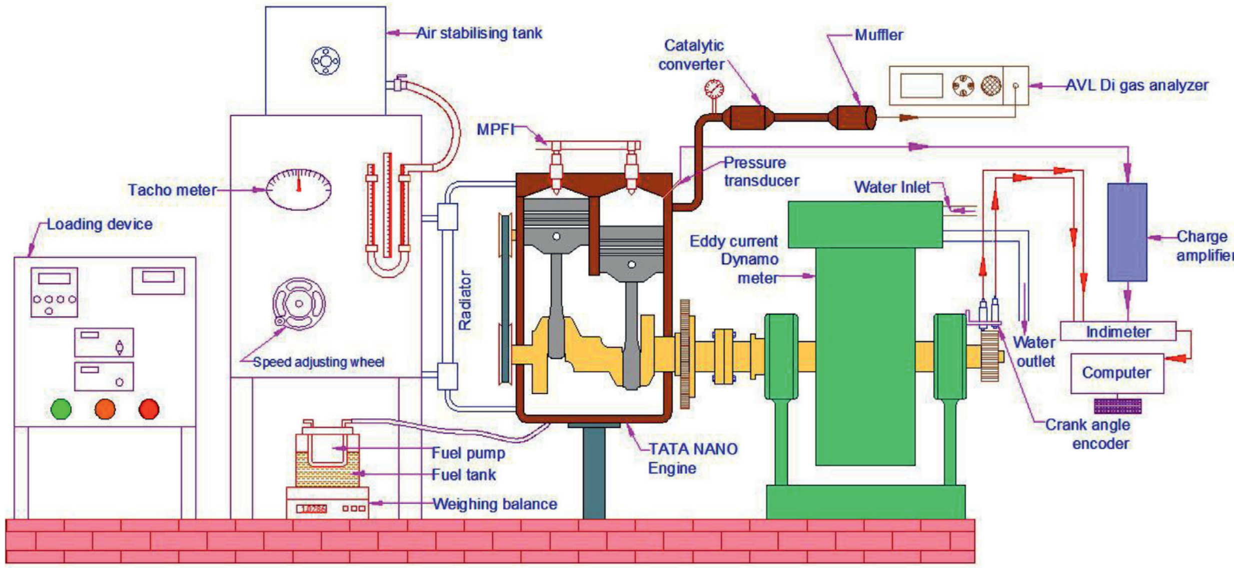

Fig. 4. Schematic Diagram of Experimental setup

gasoline blends without any catalytic convertor against the engine speed was shown in the Figure 5. The M10 blend has the maximum BTE compared to the M5 and M0, the reason is that the laminar propagation of the M10 blend is higher than that of the other blends (Yin *et al*. 2016). Thus the combustion process is enhanced with the increase in methanol concentration in the blends. It is observed from the figure that the BTE of the blends M5 and M10 at 2400rpm were 3%, and 6% higher than that of the M0 fuel.

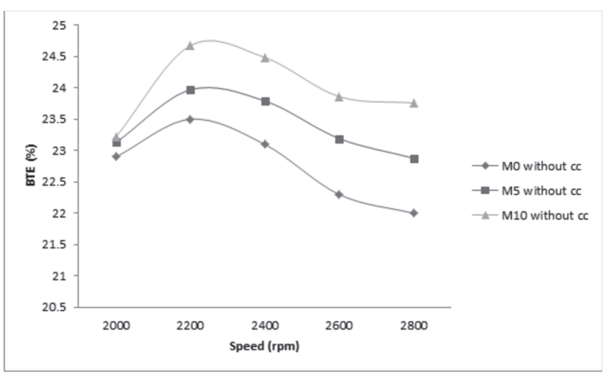

Fig. 5. BTE of various test fuel against engine speed

H. CO Emissions

Figure 6 shows the variation of CO emissions of various methanol-gasoline blends against the engine speed. At 2600rpm, the CO emissions of M5 and M10 were 6% & 10 lesser than that of the M0 fuel. CO emission is formed mainly due to the deficiency of oxygen in the combustion chamber (Yang *et al*., 2019c). Compare to M0, M5 and M10have more oxygen in it and results in the oxidation of the CO to CO_2.

The efficiency of the commercial catalytic convertor and the Cu-ZSM5 zeolite coated catalytic convertor for the oxidation of the CO emissions formed from M5 and M10 blends was performed.

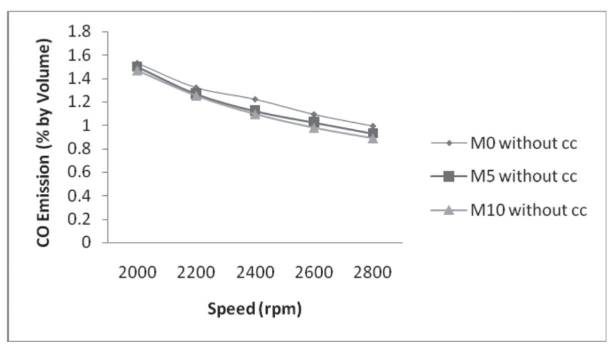

Fig. 6. CO emission of various test fuel against engine speed

The corresponding graph is shown in the Figure 7. It can be observed from the figure that the commercial as well as Cu-ZSM5 catalytic convertors reduces the CO emission from the blends, but the zeolite based catalytic convertor have the maximum efficiency. At 2400 rpm, the values of CO emissions observed by the gas analyserfor various blends with the commercial catalytic convertor is 40% lesser than that of the Cu-ZSM5 coated catalytic convertor. This is due to the conversion process of CO to CO_2 occurs both in the oxidation monolith as well as Cu-ZSM5 monolith (Liu *et al*., 2018).

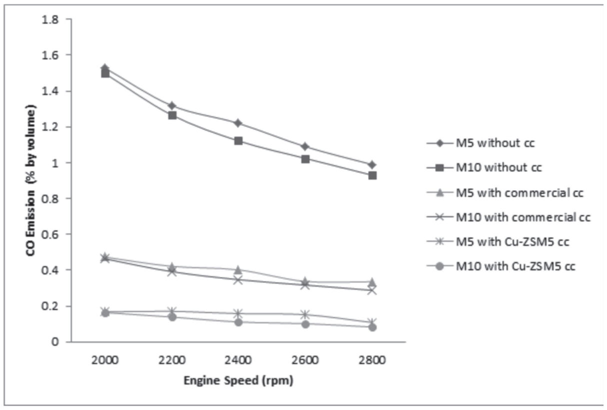

Fig. 7. CO emission of test fuels with catalytic convertors against engine speed

I. HC Emissions

The HC emission formation is decreasing with the increase in the speed for all the methanol-gasoline blends. From the Figure 8 it can be observed that there is a decrease of about 10% and 12% of HC emission formation in the blends M5 and M10 at 2400 rpm when compared with M0. The reason for the reduction of the emission with increase in the speed is due to the reduction of the flame quenching in the combustion chamber and also the temperature of the engine increases that will reduce the unburned HC (Yang *et al.*, 2019a).

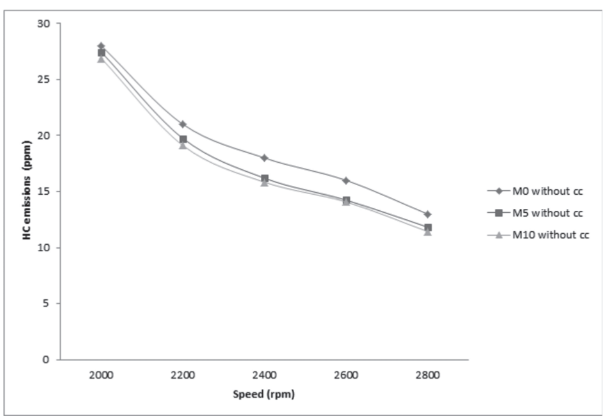

Fig. 8. HC emission of various test fuel against engine speed

The efficiency of the commercial catalytic convertor and the Cu-ZSM5 zeolite coated catalytic convertor for the oxidation of the HC emissions formed from M5 and M10 blends was performed. The corresponding graph is shown in the Figure 9. It is observed from the figure that the efficiency of the oxidation of HC emissions for Cu-ZSM5 coated zeolite catalytic convertor was better than that of the commercial catalytic convertor. At 2400 rpm, HC oxidation in the Cu-ZSM5 coated catalytic convertor is 39.3% more than that of the commercial catalytic convertor. This is because of the availability of the oxygen in the Cu-ZSM5 zeolite is more due to the dissociation of the NO_X to N_2 and O_2 (Gallastegi-Villa *et al.*, 2016). Thus the oxidation of HC takes place in both the oxidation monolith and the Cu-ZSM5 coated monolith inside the catalytic convertor results in maximum oxidation of HC compared to the commercial catalytic convertor.

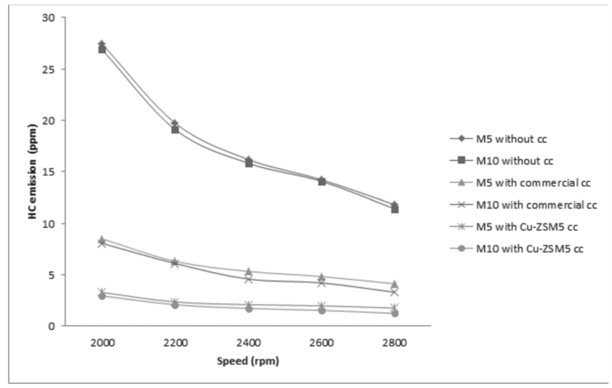

Fig. 9. HC emission of test fuels with catalytic convertors against engine speed

J. NO_X Emissions

The NO_X emission formation is increasing with the increase in the speed for all the methanol-gasoline blends. From the Figure. 10 it can be observed that there is an increase of about 7% and 17.3% of NO_X emission formation in the blends M5 and M10 at 2400rpm when compared with M0. The reason for the high emission with increase in the speed is due to the complete combustion and the rise in temperature of the engine increases the formation of the NO_X emissions (Zhang *et al*. 2019).

The efficiency of the commercial catalytic

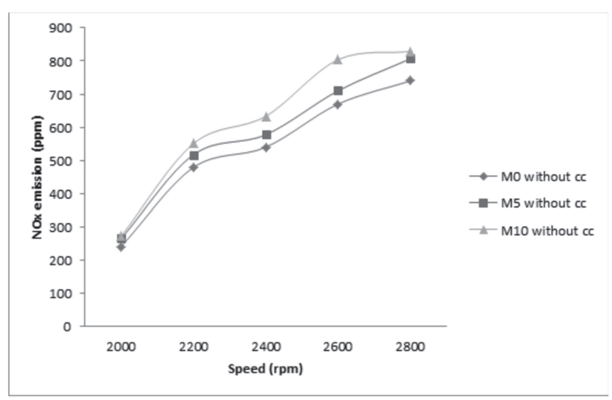

Fig. 10. NO_X emission of various test fuel against engine speed

convertor and the Cu-ZSM5 zeolite coated catalytic convertor for the reduction of the NO-$_X$ emissions formed from M5 and M10 blends was performed. The corresponding graph is shown in the Figure 11. It is observed from the figure that the efficiency of the reduction of NO-$_X$ emissions for Cu-ZSM5 coated zeolite catalytic convertor was better than that of the commercial catalytic convertor. At 2400 rpm, the NO-$_X$ reduction in the Cu-ZSM5 coated catalytic convertor is 28.16% more than that of the commercial catalytic convertor. This is because of the activity of the Cu-ZSM5 zeolite in the monolith, there will be more active sites available for the disassociation of the NO-$_X$ (Martinez-Hernandez *et al.,* 2015).

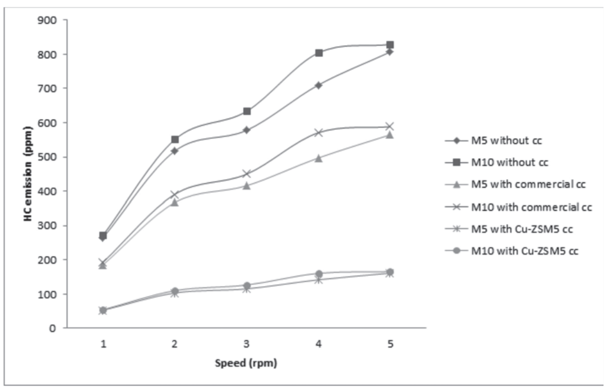

Fig. 11. NO_X emission of test fuels with catalytic convertors against engine speed

CONCLUSION

- The Cu-ZSM5 zeolite has been successfully tested for the emission reduction of the M5 and M10 methanol-gasoline blend over a wide range of speed.
- NOx conversion efficiency achieved by Cu-ZSM5 zeolite coated convertor is 28.16% more effective than the commercial catalytic convertor for all the speeds.
- The CO conversion efficiency achieved by Cu-ZSM5 coated zeolite catalytic convertor 40% more than the commercial catalytic convertor.
- The HC conversion efficiency achieved by Cu-ZSM5 coated zeolite catalytic convertor is 39.3% more than that of the commercial catalytic convertor.
- Back pressure developed is well within the acceptable limits across the catalytic bed.
- No appreciable deactivation of converter was observed, even after 100 hours of experimental examination of zeolite based catalytic converter.

REFERENCES

Azarikhah, P., Haghparast, S.J. and Qasemian, A. 2019. Investigation on total and instantaneous energy balance of bio-alternative fuels on an SI internal combustion engine. *Journal of Thermal Analysis and Calorimetry.* 137: 1681-1692.

Bacariza, M. C., Mendes, A. N., Ozhan, C., Da Costa, P. and Henriques, C. 2019. Optimizing Washcoating Conditions for the Preparation of Zeolite-Based Cordierite Monoliths for NOx CH4-SCR: A Required Step for Real Application. *Industrial & Engineering Chemistry Research.* 58 : 11799-11810.

Balzarotti, R., Cristiani, C. and Francis, L.F. 2019. Combined dip-coating/spin-coating depositions on ceramic honeycomb monoliths for structured catalysts preparation. *Catalysis Today.* 334 : 90-95.

Biswal, A., Kale, R., Balusamy, S., Banerjee, R. and Kolhe, P. 2019. Lemon peel oil as an alternative fuel for GDI engines: A spray characterization perspective. *Renewable Energy.* 142 : 249-263.

Chang, M. and Park, S. 2019. Evaporation characteristics of ethanol as alternative fuel in direct injection injector under high-temperature conditions. *Fuel.* 252 : 427-438.

Elavarasan, G. and Duraisamy, K. 2020. Effect of exhaust gas recirculation in the performance and emission characteristics of an oxygenated mustard oil biodiesel in a compression ignition engine. *Energy Sources Part A-Recovery Utilization and Environmental Effects*.

Fan, Q.H., Qi, Y.L. and Wang, Z. 2019. Impact of octane sensitivity and thermodynamic conditions on combustion process of spark-ignition to compression-ignition through an optical rapid compression machine. *Fuel.* 253 : 864-880.

Gallastegi-Villa, M., Aranzabal, A., Gonzalez-Marcos, J.A., Gonzalez-Velasco, J.R. and E. Grp Chemical Technologies, 2016. Metal-loaded ZSM5 zeolites for catalytic purification of dioxin/furans and NOx containing exhaust gases from MWI plants: Effect of different metal cations. *Applied Catalysis B-Environmental.* 184 : 238-245.

Godwin, D. J., Geo, V. E., Thiyagarajan, S., Martin, M.L.J., Maiyalagan, T., Saravanan, C.G. and Aloui, F. 2019. Effect of hydroxyl (OH) group position in alcohol on performance, emission and combustion characteristics of SI engine. *Energy Conversion and Management.* 189 : 195-201.

Iodice, P., Langella, G. and Amoresano, A. 2018. Ethanol in gasoline fuel blends: Effect on fuel consumption and engine out emissions of SI engines in cold operating conditions. *Applied Thermal Engineering.* 130: 1081-1089.

Ko, A., Woo, Y., Jang, J., Jung, Y., Pyo, Y., Jo, H., Lim, O. and Lee, Y.J. 2019. Availability of NH_3 adsorption in vanadium-based SCR for reducing NOx emission and NH3 slip. *Journal of Industrial and Engineering Chemistry.* 78 **:** 433-439.

Kumar, N. and Tomar, M. 2019. Influence of nanoadditives on ignition characteristics of Kusum (*Schleichera oleosa*) biodiesel. *International Journal of Energy Research.* 43 **:** 3223-3236.

Lin, Q. H., Chen, P.G. and Prikhodko, V.Y. 2019. Experimental Study and Model Predictive Control of a Lean-Burn Gasoline Engine Coupled With a Passive Selective Catalytic Reduction System. *Journal of Dynamic Systems Measurement and Control-Transactions of the Asme.* 141.

Liu, X. G., Li, Y., Xue, W.D., Sun, J.L. and Tang, Q. 2018. Shear-thickening behavior of Fe-ZSM5 zeolite slurry and its removal with alumina/boehmites. *International Journal of Minerals Metallurgy and Materials.* 25 **:** 682-688.

Martinez-Hernandez, A., Fuentes, G.A. and Gomez, S.A. 2015. Selective catalytic reduction of NOx with C3H8 using Co-ZSM5 and Co-MOR as catalysts: A model to account for the irreversible deactivation promoted by H_2O. *Applied Catalysis B-Environmental.* 166 **:** 465-474.

Mehla, S., Das, J., Jampaiah, D., Periasamy, S., Nafady, A. and Bhargava, S.K. 2019. Recent advances in preparation methods for catalytic thin films and coatings. *Catalysis Science & Technology.* 9 **:** 3582-3602.

Mourad, M. and Mahmoud, K. 2019. Investigation into SI engine performance characteristics and emissions fuelled with ethanol/butanol-gasoline blends. *Renewable Energy.* 143 **:** 762-771.

Rajasekar, E., Murugesan, A., Subramanian, R. and Nedunchezhian, N. 2010. Review of NOx reduction technologies in CI engines fuelled with oxygenated biomass fuels. *Renewable & Sustainable Energy Reviews.* 14 **:** 2113-2121.

Sadala, S., Dutta, S., Raghava, R., Jyothsna, T.S.S., Chakradhar, B. and Ghosh, S.K. 2019. Resource recovery as alternative fuel and raw material from hazardous waste. *Waste Management and Research.* 37 (11) **:** 1063-1076.

Schifter, I., Diaz, L., Rodriguez, R., Gomez, J.P. and Gonzalez, U. 2011. Combustion and emissions behavior for ethanol-gasoline blends in a single cylinder engine. *Fuel.* 90 **:** 3586-3592.

Thakur, A.K., Kaviti, A.K., Mehra, R. and Mer, K.K.S. 2017. Progress in performance analysis of ethanol-gasoline blends on SI engine. *Renewable & Sustainable Energy Reviews.* 69 **:** 324-340.

Wang, L., Chen, Z. M., Zhang, T.C. and Zeng, K. 2019. Effect of excess air/fuel ratio and methanol addition on the performance, emissions, and combustion characteristics of a natural gas/methanol dualfuel engine. *Fuel.* 255.

Yang, J.C., Roth, P., Durbin, T. and Karavalakis, G. 2019a. Impacts of gasoline aromatic and ethanol levels on the emissions from GDI vehicles: Part 1. Influence on regulated and gaseous toxic pollutants. *Fuel.* 252 **:** 799-811.

Yang, J. C., Roth, P., Durbin, T.D., Shafer, M.M., Hemming, J., Antkiewicz, D.S., Asa-Awuku, A. and Karavalakis, G. 2019b. Emissions from a flex fuel GDI vehicle operating on ethanol fuels show marked contrasts in chemical, physical and toxicological characteristics as a function of ethanol content. *Science of the Total Environment.* 683**:** 749-761.

Yang, J. C., Roth, P., Zhu, H.W., Durbin, T.D. and Karavalakis, G. 2019c. Impacts of gasoline aromatic and ethanol levels on the emissions from GDI vehicles: Part 2. Influence on particulate matter, black carbon, and nanoparticle emissions. *Fuel.* 252 **:** 812-820.

Yin, C. B., Zhang, Z. D., Xie, N.L., Sun, Y.D. and T. Sun, 2016. Knock In Dual-Fuel Diesel Combustion With An E85 Ethanol/Gasoline Blend By Multi-Dimensional Simulation. *International Journal of Automotive Technology.* 17 **:** 591-604.

Yoldi, M., Fuentes-Ordonez, E.G., Korili, S.A. and Gil, A. 2019. Zeolite synthesis from industrial wastes. *Microporous and Mesoporous Materials.* 287 **:** 183-191.

Yuan, Q., Zhang, Z.Y., Yu, N.S. and Dong, B. 2018. Cu-ZSM-5 zeolite supported on SiC monolith with enhanced catalytic activity for NH3-SCR. *Catalysis Communications.* 108 **:** 23-26.

Zaharin, M. S. Abdullah, M., N. R.. Masjuki, H.H., Ali, O.M., Najafi, G. and Yusaf, T. 2018. Evaluation on physicochemical properties of iso-butanol additives in ethanol-gasoline blend on performance and emission characteristics of a spark-ignition engine. *Applied Thermal Engineering.* 144 **:** 960-971.

Zhang, B. and Sarathy, S.M. 2016. Lifecycle optimized ethanol-gasoline blends for turbocharged engines. *Applied Energy.* 181 **:** 38-53.

Zhang, P., Su, X., Chen, H., Geng, L.M. and Zhao, X. 2019. Experimental investigation on NOx and PM pollutions of a common-rail diesel engine fueled with diesel/gasoline/isopropanol blends. *Sustainable Energy & Fuels.* 3 **:** 2260-2274.