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Experimental investigation on the effect of UWSinjectionon NO_x reduction efficiency of urea-SCR system for marine diesel engine

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Abstract-*Oxides of nitrogen (NO_x) emitted from operating marine diesel vessels which negatively affect human health and environment are considered a global pollution problem. They areregarded a major reason for photochemical smog and acid rain formation. Therefore, IMO (international maritime organization) has issued strict regulations to reduce NO_x emissions from marine diesel engines. In order to comply with these strict requirements, differentafter-treatment technologies for NO_xemission abatementhave beenintroduced and SCRproved to beone of the most effectivemethods for marine diesel engines. Improving SCR performance and increasing NO_xabatement efficiency have been a topic of study for various researches.*

In thiswork, an experimental investigation onurea SCR systemiscarried out to examinethe effect of UWS injection in terms ofinjector position andinjectordirection on NO_x reduction efficiency under various engine loads on a four stroke medium speed marine diesel engine. Results show that injecting UWS at 5D location upstream of SCR entrance has achieved the highestNO_x reduction efficiencyof 70% due to longerresidence time which promotesmixing and chemical reaction between droplet and exhaust gas. Reversed injection at 30^o direction showed better efficiency over positive injection directions due to stronger interaction of spray into incoming gas flowleading to better atomization and homogeneous mixing between droplet and flow. Efficiency is also improved while injecting at 90^oangle due to less wall impingement since the spray is axially distributed.As engine load increased to 75% full load, efficiency is increased to the maximum value whereas at full load, efficiency is observed to reduce due to increased gas flow inertia that hinders a deep penetration of the injected droplets into the exhaust gas.Based on these results, the present work helpsin providing basic guidelineson the optimal injection variables for an optimizedSCR performance.

Keywords: *SCR, marine diesel engine, UWS, injector, position, direction, performance*

I. Introduction

Compared to gasoline engines, diesel engines have higher thermal efficiency and better fuel economy. However, diesel engines are considered a major contributor to air pollution. In maritime sector, ships annually contribute to 30% of global NO_x emissionswhereapproximately 70% of emissions occur within 400 km of land [1]. It could be transported over long distances in the atmosphere so that their negative impacts are not limited to the source of emissions.

Due to increasing awareness on negative impacts of oxides of nitrogen on health and environment, international maritime organization (IMO) has issued stringent regulations to control NO_x in diesel exhaust gas emissions emanating from operating marine vessels. On 1st January 2016, Tier III regulation came into effect where approximately 80% NO_x emission reduction efficiency is required [2]. In order to comply with these regulations, effortswere made to develop NO_x after-treatment technologies such as SNCR (selective non catalytic reduction), LNT (Lean NO Trap Catalyst), and plasma-facilitated catalysis (PFC). Among all these technologies, selective catalytic reduction (SCR) is the most preferred mainstream technology for NO_x emissions reduction in heavy duty diesel engines. The word "selective" indicates that SCR only absorbs ammonia for NO_x emissions reduction in the presence of high oxygen concentrations by using an appropriate catalyst and an effective reductant. Urea is one of the most preferred reducing reagents because of easy handling with high selectivity toward NO_x.

SCR was first applied in Japan in late 1970s for stationary power plants. At mid of 2000s, it was used for mobile diesel engines [3]. Nowadays SCR is a popular technique for marine, heavy and light duty diesel vehicles.

II. Literature review

Many researchers have investigated the influence of injection parameters on SCR performance such as injector location and injection angle. Some of these research works are demonstrated as following:

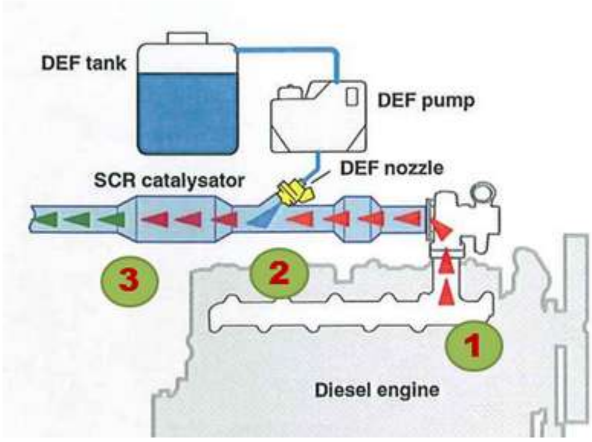

Figure 2: SCR system configurations

Kim et al. [3] investigated thermal decomposition of UWS dropletsinto ammonia in order to design a mixing chamber in SCR system of the optimal size and geometry. From the experimental and numerical investigation they observed the characteristics

Jeong et al. [4] presented a numerical model for the optimal shape and location of UWS injector for SCR system in heavy duty diesel engine. They investigated the effect of injector location, injector shape and injection pressure on ammonia uniformity index and the evaporation rate of aqueous urea solution within exhaust gas tailpipe and the monolith of SCR catalyst.

Ericson [5] build a complete diesel engine/SCR system model comprising of many sub-models to investigate the effects of varied EGR rate, injection pressure, injection timing and urea injection on NO_x formation and urea consumption. He showed that the highest NO_x conversion was achieved at low speeds and high torque. Efficiency was reduced at high space velocities and at low loads the limitation was the temperature.

Tian et al. [6] presented a numerical model of UWS injection and detected the effect of four conditions on ammonia mass fraction upstream to SCR converter. The conditions are: injection relative velocity, spray cone angle, turbulence intensity and exhaust gas velocity. The numerical results exhibited that the ammonia mass distribution was enhanced by increasing the distance between injector and monolith entrance, increasing the injection relative velocity, increasing the exhaust disturbance and decreasing the exhaust velocity. The residence time of ammonia was influenced by the exhaust velocity; means the diffusion time of ammonia was short when the velocity was high.

Shah et al. [7] evaluated SCR performance in terms of different operating parameters. Experimental results showed that SCR system efficiency was greatly influenced by catalyst temperatures and GHSV.

To the best of authors' knowledge, researches investigating the behavior of side UWS injector of multi-hole nozzle in SCR system are not easy to find. Therefore, experimental test was carried out to examine the effect of injection on exhaust gas flow and SCR behavior in the present work.

III. SCRstructure and synthesis

SCR converteris a monolith consistingof parallel channels running axially through the catalyst substrateseparated by thin walls coated with the active material.The monolith could be either ceramic extrusions or corrugated metal foil assemblies as shown in figure3. Each type is typically coated with an intermediate layer of inorganic oxides called washcoat in order to provide the high surface area which is required for active material[8].Exhaust gas flows through the channels to get in touch with the catalyst deposited on the channel walls. Most substrates in diesel applications have cell densities in the range of 300-400 cpsi range.

Commercial V_2O_5-WO_3/TiO_2(vanadium-tungsten/titanium) catalyst has been widely used for the SCR system.Vanadiumbased catalyst has been applied in mobile application as well as heavy duty diesel engines since 2005 [9]. It is mainly active at temperature range of 300^{o}C -400^{o}C with relatively large amount of WO_3. It typically consists of anatase(mineral form of TiO_2)as the support material, WO_3 as anactivity and stability promoter and around 2% wt.V_2O_5as the active redox (reduction and oxidation) material [10].Cordierite ceramic is a magnesium aluminum silicate material that has been widely used in applications where thermal shock resistance is important.

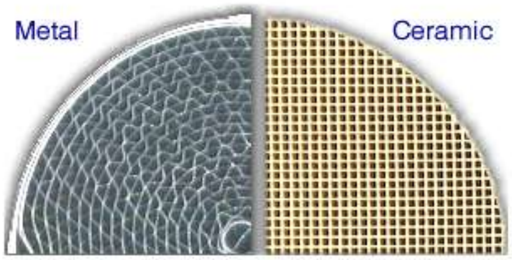

Figure 3: Monolithic Catalyst Substrates

IV. Experimental setup and procedure

In this work, experiments are carried out on four-stroke medium speed marine diesel engine. It is a twin cylinder, water cooledengine coupled with an eddy current dynamometer for load controlling as shown in table 2.SCR system has been specificallydesigned for this engine andattached at the lower side of the exhaust pipe.DOC is fitted upstream of SCR andAVL 5 gas analyzer is used for measuring NO_x before and after SCR substrate.Figures 4-5 show the experimental setup and a schematic diagram of engine test rig with urea-SCR system. Figures 6-7-8-9 show SCR before and after installation on test rig, DOC and AVL gas analyzer.SCR specifications are shown in table 4.

Four different injector locations upstream of SCR inlet were consideredand examined for experimental investigations namely 1.5D, 3D, 5D and 7D where D: exhaust gas tailpipe diameter.

After deciding the optimum location of UWS injection, four injection directions were inspected to specify the effect of changing injection direction on NO_x reduction efficiency. The injection anglesconsideredare namely: -30^o, -60^o, 90^o, 30^o investigated at different engine loadings. Engine loadings are varied from 25% to full load as shown in table 3.Figure 10 show the different injection positions upstream of SCR entrance.

Figure 4: Experimental setup

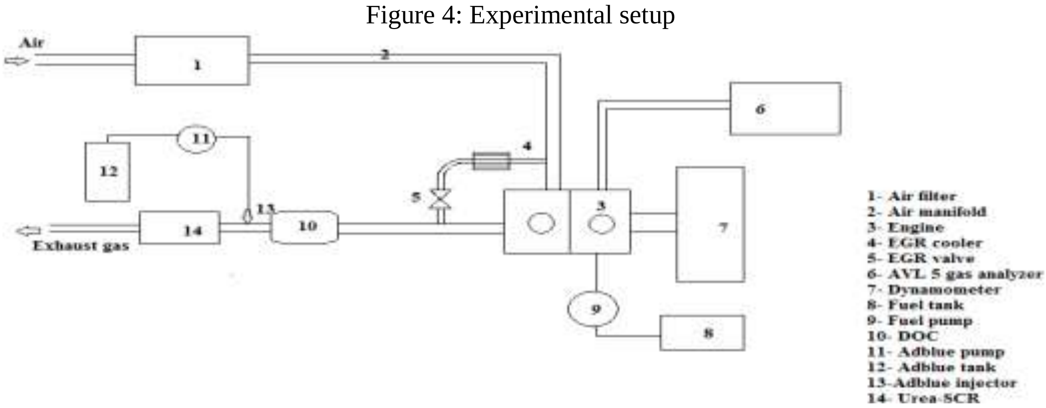

Figure5: Schematic diagram of engine test rig with Urea-SCR system

Figure 6: SCR monolith catalyst

Figure7: SCR after attaching to the injection system

Figure8: DOC

Figure 9: AVL 5 gas analyzer and smoke meter

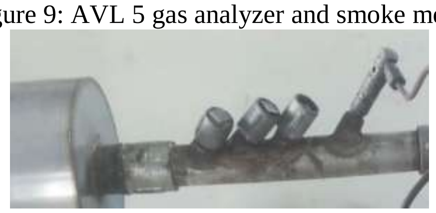

Figure10: Different injection positions upstream of SCR inlet

Table 2: Engine configurations

Items	**Description**
Engine Make	Simpson S 217
Engine Type	Vertical inline diesel engine,4 stroke, Twin cylinder
Engine power	21 kW
Bore stroke	91.44 mm127 mm
Compression ratio	18.5:1
Displacement	1670 cc
Engine rated speed	1200 rpm
Exhaust pipe diameter	38.1 mm
Nozzle hole diameter	0.225 mm

Table 3:exhaust gas specifications

	Load (%)	Inlet temperature (°C)
Speed (rpm) 1200	25	250
	50	325
	75	410
	100	472

Table4:SCR substrate specifications

Material	Chemical composition	Length(mm)	Diameter (mm)	Volume (L)	Cell Density (CPSI)	Cell geometry	Cell side length (mm)	Porosity (%)	Wall thickness (mm)
Cordierite ceramic	$2MgO$-$2AL_2O_3$-$5SiO_2$	152.4	190.5	4.34	400 standard (STD)	square	1.103	75%	0.167

V. Result and discussion

5.1. Effect of injector location on NO_x reduction efficiency

The results show that NO_x reduction efficiency gradually increases as the injector is located more far from the entrance of the SCR monolith. Highest efficiency is attained at 5Dinjection location with value of 66% at 90°injection angleand 75% engine load as shown in figures 11. The reason behind this is that the greater distance between the injector and the monolith face allows longer interaction time between the droplet and the hot exhaust gas, which promotes the efficiency of mixing rate and leads to better atomization. After 5D, efficiency is observed to start reducing which is interpreted due to increased gas flow inertia that hinders a deep penetration of the injected droplets into the exhaust gas.

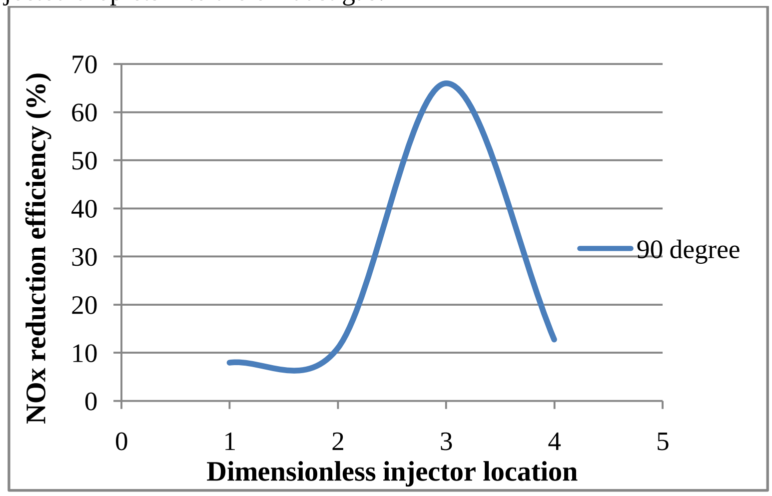

Figure 11: effect of injection location on NO_x reduction efficiency at 90 degree and 75% engine load

5.2. Effect of injectionangle on NO_x reduction efficiency

Theinjection nozzle used for the experiments has six holesequally spaced in circumference. This multi- hole nozzle spray has theadvantage of extended space utilization compared to a single hole nozzle which results inmore uniform droplets distribution and higher urea to ammonia conversion.Multi- hole nozzle is more appropriate for distributing the effective material and providing better interaction with exhaust gas.

Oneof examined injection anglesis positive (30°)where the active material is being injected in the same direction withexhaust gas flow.Injected spray oftwo other injection angles (-30°,-60°) arebeing injected opposite to flow direction. The spray under negative injection angle owns a much stronger interaction with gas flow because the reversed injection of urea droplets into exhaust gas stream causes anintensive breakup due to the increase in friction force and relative velocity against the incoming exhaust gas.

As urea-solution spray under negative injection angles interacts more violently with incoming gas flow, it is hard to evaluate its effect on droplet distribution compared to positive injection angles. High efficiency is achieved at 90 injection angle and this could be explained to less possibility of wall impingement due to spray axial distribution.The highest efficiency scored is 70% achieved at -30 injection angle at 75% engine load as shown in figure 15.

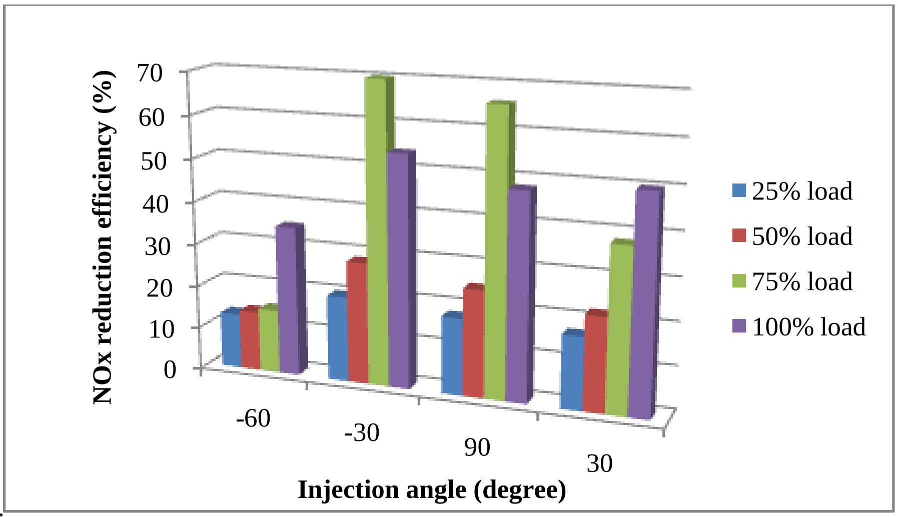

Figure15: Effect of injection angle on NO_x reduction efficiency at different engine loads

5.3. Effect of engine load on NO_x reduction efficiency

As the engine load increases from 25% to 100%, SCR efficiency is observed to increase and the highest NO_x reduction efficiency value achievedis 70% at 75% engine load (410^{o}C).At full load, increased gas flow inertiaprevents a deep penetration of the injected droplets into the exhaust gas stream which is the reason behind efficiency reduction at 100% engine load. The effect of engine load on NO_x reduction efficiency at different injection locations is shown in figure 16.

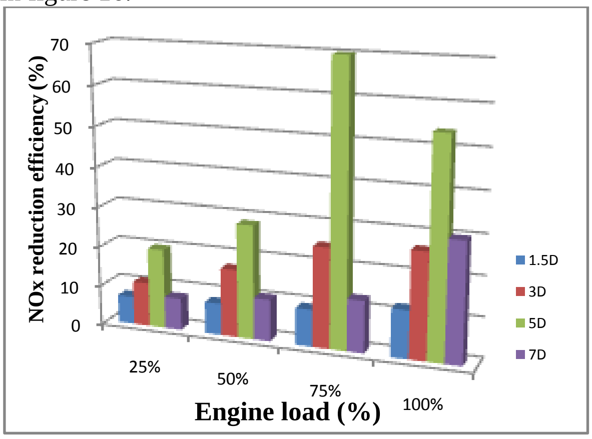

Figure16: Effect of engine loads on NO_x reduction efficiency at different injection locations

VI. Conclusions and future perspectives

In this work, an experimental investigationonSCR performance optimization was carried out to examine the effect of UWS injection on NO_x reduction efficiency in terms ofinjection location and injection direction at different engine loads and following conclusions arederived:

As injection location gets far upstream of SCR entrance, NO_x reduction efficiency is increasedbecause oflonger residence time which enhances mixing and chemical reactionbetween spray droplets and hot exhaust gas. Reversed injection at 30 angle shows the highest efficiency at all loads due to the increase in friction force and relative velocity of droplets against the incoming exhaust gas.Injection at90 angle leads to less wall impingement due to spray axial distribution which promotes efficiency.

As engine load increases, NO_x reduction efficiency increasesandthe maximum value is scored at 75% engine load.It is also noticed that efficiency reduces when engine load increases beyond 75%due toincreased gas flow inertia which inhibits the injected droplets from deep penetration through the exhaust gas stream

Future works on SCR performance enhancement could be continued by studying the effect ofmodifying SCR geometryon NO_x reduction efficiency in terms of uniform spray distribution and urea conversion. Flow characteristics could also be enhanced by incorporating a static mixer downstream of injector for improving urea conversion which could be validated through numerical investigation.

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