

Numerical Analysis of the Effect of Static Mixer on SCR System Performance of Marine Diesel Engine

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Abstract:

Due to increasing awareness of negative impacts of emissions of NO_x on public health and the environment, IMO has issued stringent rules to reduce NO_x emissions from marine vessels. Tier III is the most stringent standard where around 80% NO_x reduction efficiency is required. In order to satisfy these rules, NO_x abatement technologies were developed and SCR is considered one of the most effective and promising methods to meet such regulations. In the current work, SCR system is fitted to a medium speed marine diesel engine and UWS is centrally injected from 6-hole nozzle positioned 5D upstream of SCR entrance. Two different types of static mixers are installed upstream of SCR entrance namely blade mixer and flapper mixer to investigate their effect on two parameters namely urea conversion efficiency and uniformity index (UI). Four different configurations are investigated and compared to each other's as listed in table 1. These four cases are researched at three different exhaust gas velocities. Results revealed that the best urea conversion efficiency is achieved when both mixers are installed with a value of 91.7%, while flapper mixer resulted in 10.86% higher urea conversion efficiency over the blade mixer. The reason behind this is due to the bigger contact surfaces between exhaust gas flow and flapper mixer, more ammonia and flow come in touch with each other's leading to better mixing quality. UI increases along with urea conversion and the maximum value achieved is 92.8% at 8.3 m/s when both mixers are installed. On the other hand, flapper mixer achieved 91.9% UI which is 2.79% higher than that achieved by blade mixer. At smaller exhaust velocities, higher UI and higher urea conversion efficiency are achieved due to more residence time which enhances mixing and chemical reactions.

Keywords — Static mixer, SCR, Performance, Marine diesel engine, Urea conversion, UI.

I. INTRODUCTION

Over 90% of global trade is carried by ship industry all over the world [1]. It is the most safe and cost effective method for long distance transportation. On the other hand, Maritime sector accounts for up to 30% of the annual global NO_x emissions which are considered a major air pollution problem that threatens human health and environment [2]. They contribute to acid rain formation and photochemical smog which can damage crops, forests, wildlife populations, and cause respiratory illnesses.

Marine vessels are also an important source of GHG emissions which contribute to climate change [3].

Shipping emissions are expected to double by 2050 and harmful effects will continue to rise [4]. Therefore, IMO assigned limits on the permissible amounts of NO_x emissions in three standards namely Tier I, Tier II and Tier III. Tier III standard entered into force after 1st January 2016 and it is the strictest regulation where 80% NO_x reduction efficiency is required [5].

In order to comply with these regulations, efforts were 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 for 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 ease in handling with high selectivity toward NO_x.

SCR was first applied in Japan in late 1970s for stationary power plants. During mid 2000s, it was used for mobile diesel engines [6]. Nowadays SCR is a popular technique for marine, heavy and light duty diesel vehicles.

Static mixers are widely used in SCR system upstream of converter in order to improve its performance. It influences flow characteristics and promotes conversion of urea into ammonia because it induces vortex flow which increases turbulence intensity that enhances mixing between ammonia and exhaust flow.

Choi et al. [7] proved that adding a mixing unit upstream of SCR monolith has improved flow characteristics and ammonia conversion efficiency. A static swirl mixer with a mixing chamber are considered as a mixing unit. The mixer recirculates the flow resulting in higher turbulence. On the other hand, the chamber increased the residence time of injected UWS leading to higher ammonia conversion rate due to well distributed turbulence and high value of uniformity index and consequently more nitrogen oxides reduction efficiency resulted.

Choi et al. [8] researched the effect of mixer on ammonia conversion efficiency for marine diesel engine. Results exhibited an improvement in ammonia conversion efficiency when the particle distribution met with high turbulence intensity area despite the non-uniform distribution. Residence time was also correlated to recirculation degree and droplet evaporation rate which affected urea decomposition.

Park et al. [9] investigated the effect of mixer on ammonia uniform distribution of SCR system in a passenger car. They utilized STAR-CCM+7.06 code to execute 3DEulerian-Lagrangian CFD simulation for internal flow and spray characteristics in front of SCR. They

proposed a method for wall wetting reduction around the injector to prevent injector blocks.

Fournier et al. [10] researched static mixer design enhancement for heavy duty diesel engine SCR system performance optimization. They proved the developed mixer design could achieve optimum ammonia distribution simultaneously with less wall-film mass and pressure drop.

However, there is insufficient research on the relationship between flow mixing characteristics in marine engine fields. In the present work, four types of geometry are selected to simulate the effect of installing two different structures of static mixer in terms of urea conversion efficiency and UI.

I. NUMERICAL PROCEDURE

In this work, ANSYS Fluent 15 is utilized for modeling SCR system and analyzing its performance. Exhaust gas flow is assumed to be incompressible and its motion is governed by Reynolds-Averaged Navier-Stokes equations (RANS) which represents the conservation of mass, momentum, energy and chemical species mass fraction as following:

Mass conservation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0$$

Momentum conservation:

$$\frac{\partial(\rho \mu_i)}{\partial t} + \frac{\partial(\rho \mu_i \mu_j)}{\partial x_i} = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}$$

Energy conservation:

$$\frac{\partial \rho h}{\partial t} + \frac{\partial(\rho u_i h)}{\partial x_i} = -\frac{\partial \tau_{ij} \mu_j}{\partial x_i} + \frac{\partial}{\partial x_i} \left(\lambda \frac{\partial T}{\partial x_i} \right)$$

Chemical species mass fraction:

$$\frac{\partial \rho Y_k}{\partial t} + \frac{\partial(\rho u_i Y_k)}{\partial x_i} = -\frac{\partial \tau_{ij} \mu_j}{\partial x_i} + \frac{\partial}{\partial x_i} \left(\rho D_k \frac{\partial Y_k}{\partial x_i} \right)$$

Where ρ is density, t is time, u_i is velocity, P is static pressure, τ_{ij} is stress tensor and μ is dynamic viscosity.

Euler-Lagrangian approach is employed for modeling multi-phase flow when more than one fluid exists. Exhaust gas flow is considered as continuous phase modeled using Eulerian approach, while injected particles are regarded as the dispersed phase modeled by applying Lagrangian approach.

Discrete phase model (DPM) is utilized to describe the behavior of UWS spray. The injected particles are multicomponent and assumed to follow Rosin-Rammler diameter distribution which has the following expression:

$$1 - Q = \exp\left(-\left(\frac{D_p}{X}\right)^q\right)$$

Where Q is the portion of the total volume holding drops with a diameter less than D_p , q is a measure of the spread in size and x is the reference diameter.

II. NUMERICAL APPROACH

Geometry is created in ANSYS workbench and mesh is generated in ANSA. Mesh is tetrahedral with one million cells. The domain close to the mixer is meshed using a finer mesh to properly resolve the gradients in this region as shown in figure 1 and figure 2.

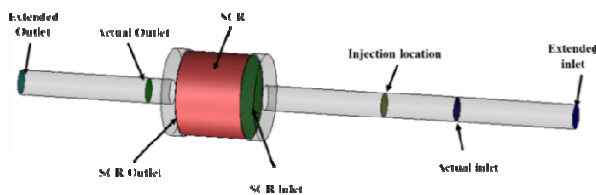


Fig. 1 SCR Geometry created in ANSYS Workbench

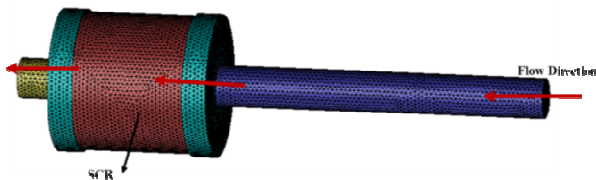


Fig. 2 SCR mesh created in ANSA

Two types of static mixers are considered for the study namely flapper mixer of 20 vanes and blade mixer of 8 vanes as shown in figure 3 and figure 4. Four cases are researched to investigate the effect of different configurations of static mixer on SCR performance as shown in table 1. In first case, no mixer is considered as shown in figure 5. In second and third cases, both mixers are installed at a position of 2.5D downstream of adblue injector as displayed in figure 6 and figure 7 where D is exhaust pipe diameter. In fourth case, blade mixer is installed at 1.5D upstream of SCR entrance while the flapper mixer is positioned at 3D upstream of SCR entrance as shown in figure 8. Both mixers are developed for this study with several unique features such as simple design for production and the flexibility in installation and controlling the mixer volume in the exhaust pipe. The temperature of the exhaust gas is set to 673K with three different exhaust inlet velocities of 17, 10.8 and 8.3 m/s.

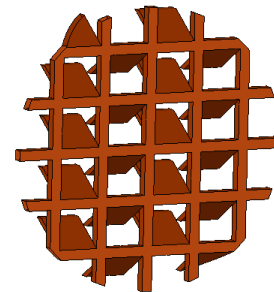


Fig.3 Flapper mixer

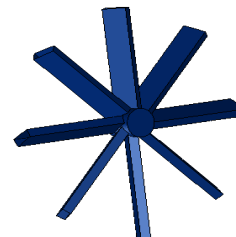


Fig. 4: Blade mixer

TABLE 1 CLASSIFICATION OF MIXER CONFIGURATIONS

Case number	
1	No mixer
2	One blade mixer
3	One flapper mixer
4	One blade mixer and one flapper mixer

Fig.8 SCR system with one flapper mixer and one blade mixer

III. RESULTS AND DISCUSSION

The results obtained show that installing a static mixer enhances SCR system performance in terms of urea conversion efficiency and uniformity index (UI) as depicted in figure 9 and figure 10. In case of installing blade mixer, urea conversion efficiency obtained is 75.1% which is 20.54% higher comparing to the case without a static mixer, while flapper mixer resulted in 10.86 % higher urea conversion efficiency over blade mixer. The reason behind this is the bigger contact surfaces between exhaust gas flow and flapper mixer leading to much ammonia and flow to come in touch with each other's resulting in better mixing quality. The best urea conversion efficiency is obtained when both mixers are considered with a value of 91.7% at exhaust inlet velocity of 8.3 m/s.

UI increases along with urea conversion and the maximum value achieved is 92.8% at 8.3 m/s when both mixers are installed. On the other hand, flapper mixer achieved 91.9% UI which is 2.79% higher than that achieved by blade mixer. The vortex flow promotes hydrolysis and thermolysis by increasing the mass fractions of NH₃ and HNCO which enhance NO_x reduction efficiency as shown in figure 11. At smaller exhaust velocities, higher UI and higher urea conversion efficiency are achieved due to more residence time which enhances mixing and chemical reactions.

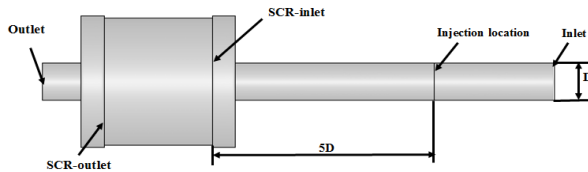


Fig.5 SCR system without a mixer

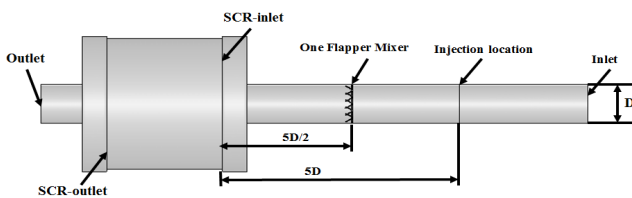


Fig.6 SCR system with one flapper mixer

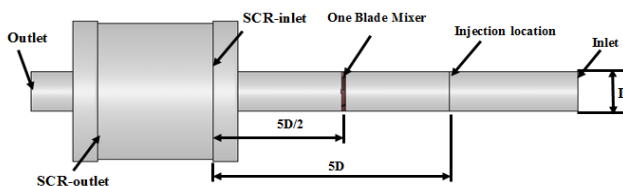


Fig.7 SCR system with one blade mixer

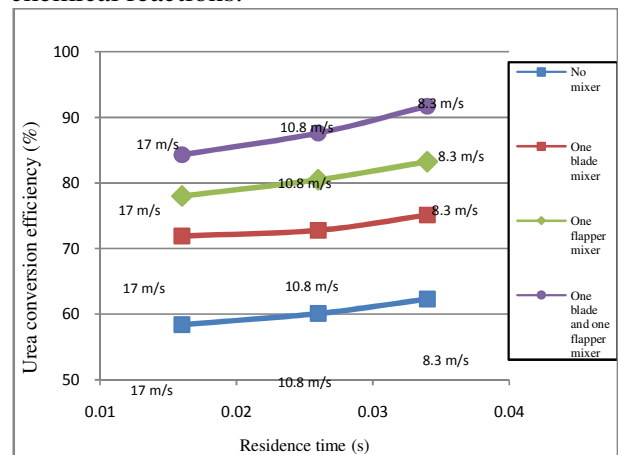
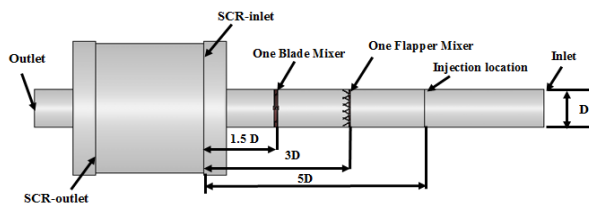


Fig.9 Simulation results of urea conversion efficiency to residence time at different mixing configurations

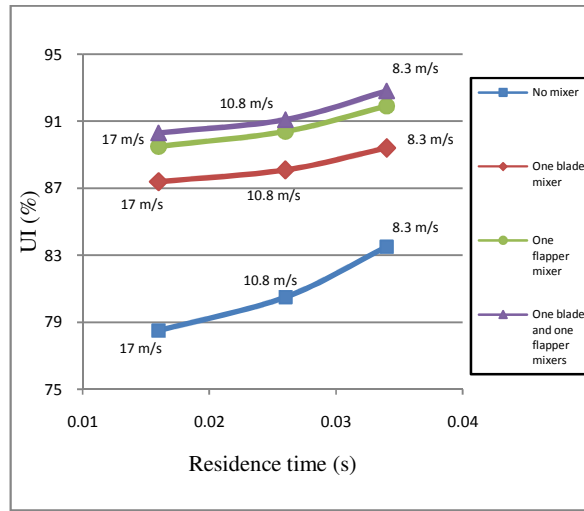


Fig.10 Simulation results of UI to residence time at different mixing configurations

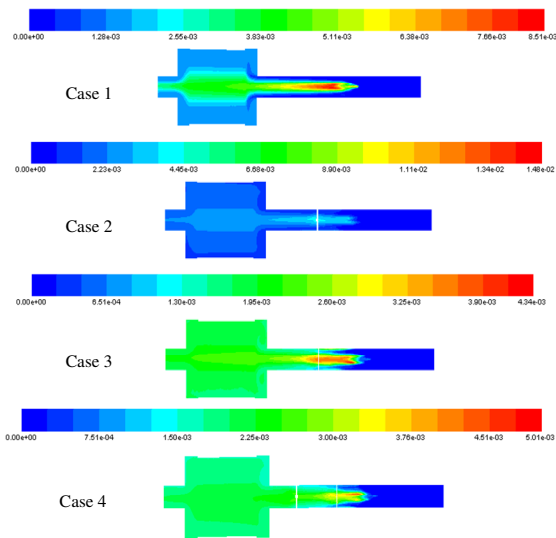


Fig.11 Contours of mass fraction of NH₃

IV. CONCLUSIONS

Selective Catalytic Reduction technology (SCR) is considered one of the most efficient solutions to reduce increased NO_x emissions in order to

satisfy the stringent NO_x emissions abatement regulations. SCR performance is evaluated through numerical investigation of urea conversion efficiency and UI in terms of spray characteristics. Results obtained show that the best results of urea conversion efficiency and UI are achieved when both mixer types are installed. While flapper mixer achieved better results over blade mixer due to its structure which provides large contact surface between urea and exhaust gas so that higher conversion efficiency could be obtained. At smaller exhaust velocities, higher UI and higher urea conversion efficiency are achieved due to more residence time which enhances mixing and chemical reactions. In future work, control gate leaves could be installed along with static mixer in order to enhance velocity distribution at SCR entrance while low pressure drop is achieved.

REFERENCES

- 1- Maria G. Burns, Logistics and Transportation Security: A Strategic, Tactical, and Operational Guide to Resilience 2015, ISBN 9781482253078
- 2- European Policy Center, "Reducing CO emissions from shipping - rethinking European policies", 18 September 2012
- 3- Linda R. Berg, Mary Catherine Hager, David M. Hassenzuhl, Visualizing Environmental Science, Wiley, 22-Sep-2010 - Science - 489 pages
- 4- Carlos GuedesSoares, T.A. Santos, Maritime Technology and Engineering, September 30, 2014 by CRC Press - ISBN 9781138027275
- 5- <http://www.dieselnet.com/standards/inter/imo.php>
- 6- Nova, Isabella, Tronconi, Enrico, Urea-SCR Technology for deNO_x after Treatment of Diesel Exhausts, 2014, DOI: 10.1007/978-14899-8071-7.
- 7- Choi C, Sung Y, Choi GM, Kim DJ. Numerical analysis of NO_x reduction for compact design in marine urea-SCR system, Int. J. Nav. Archit. Ocean Eng. 2015; 7:1020-1033

- 8- Choi C, Sung Y, Choi GM, Kim DJ. Numerical Analysis of Urea Decomposition with Static Mixers in Marine SCR System. Journal of Clean Energy Technologies 2015; 3(1):39-42.
- 9- Park K, Hong CH, Oh S, Moon S. Numerical Prediction on the Influence of Mixer on the Performance of Urea-SCR System. World Academy of Science, Engineering and Technology. International Journal of Mechanical. Aerospace. Industrial, Mechatronic and Manufacturing Engineering 2014; 8(5).
- 10- Fournier O, Yamada T. Development of Static Mixer Device for Heavy Duty Diesel Engine SCR After-treatment System. Calsonic Kansei Technical 2012; 9.