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NUMERICAL ANALYSIS OF THE EFFECT OF UWS INJECTION CHARACTERISTICS ON SCR SYSTEM PERFORMANCE FOR MARINE DIESEL ENGINE

Jaedaa Abdulhamid[*]

Prof T.V.K. Bhanuprakash

Prof. P.V.J. Mohan Rao

Abstract

International maritime organization (IMO) has adopted strict regulations to control harmful oxides of nitrogen emissions from operating 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 that can meet such regulations.

SCR technology depends on injecting urea water solution (UWS) to exhaust gas flow upstream of SCR entrance to generate ammonia which is the effective material for chemical reactions inside SCR converter. Studying the phenomena taking place between UWS injection point and SCR entrance helps creating better understanding of SCR converter chemistry which supports SCR performance evaluating.

In this paper, a numerical model of SCR converter for medium speed marine diesel engine is presented. Two substantial parameters are introduced for SCR performance evaluation namely urea conversion efficiency and uniformity index (UI). These two parameters are not easy to experimentally investigate due to number of technical limitations. Hence, the evaluation

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[*] Department of Marine Engineering, A.U. College of Engineering (A), Andhra University
Visakhapatnam, A.P., (India)

parameters are numerically examined in terms of specific injection characteristics namely droplet size, spray angle, and injection velocity.

Results reveal that relatively small-sized droplets are required to achieve higher urea conversion efficiency and UI due to better UWS droplet atomization and enhanced evaporation. Evaluation parameters are also enhanced at elevated injection velocities due to better mixing with exhaust flow. However, higher injection velocity will have negative effect on the flow distribution due to small residence time leading to less chemical interaction between ammonia and oxides of nitrogen. Better spatial distribution is achieved at large injection angles, but wall impingement will negatively influence efficiency at too big injection angles.

Keywords: numerical analysis, ANSYS Fluent, UWS injection, Urea SCR, performance

1- 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 also contribute to largeGHG emissions which are responsible for climate change [3].

Shipping emissions are expected to double by 2050and negative impacts will continue to rise [4]. Therefore, IMO assigned limits on permissible amounts of NO_xemissions in three standards namely Tier I, Tier II and Tier III. Tier III standard entered into force after1stJanuary2016 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.

2- 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 isthe portion of the total volume holding drops with a diameter less than D_p, q is a measure of the spread in size andx is the reference diameter.

2.1. Geometry and mesh generation

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.

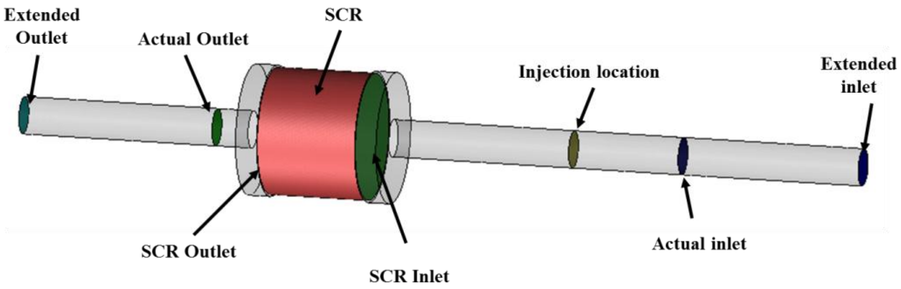


Fig. 1: SCR Geometry created in Ansys Workbench

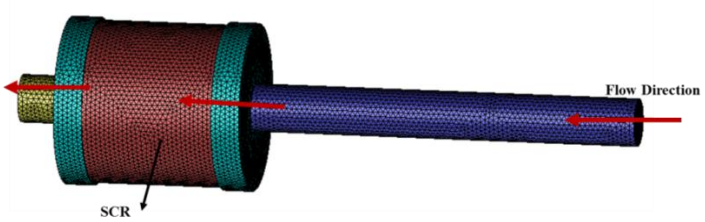


Fig. 2:SCR mesh created in ANSA

2.2. CFD methodology

The present work is a numerical study for SCR performance of medium speed marine diesel engine and the tested SCR converter is specifically designed for this engine.

In order to estimate the efficiency of SCR performance, it is important to investigate phenomena taking place between injection point and SCR entrance. Two estimation factors are considered for numerical study in terms of different injection characteristics namely urea conversion efficiency and uniformity index (UI).

These two factors are not easy to experimentally investigate due to some technical limitations in the lab so that they are numerically examined. Central injector of six-hole nozzle is utilized in order to investigate the effect of injection characteristics on SCR performance. By improving these two factors, NO_x reduction efficiency is also improved. A short introduction about these two parameters are presented below:

2.2.1 Urea Conversion Efficiency

Urea conversion efficiency is defined as the ratio of the generated mount of active materialwhich is ammonia to the maximum amount of ammonia when urea totally decomposes and it could be expressed by the following formula:

$$\eta = \frac{\max(\sum_{k=1}^{k_{max}} m(k)_{gen}^{t_s})_{t_s=1,2,3,....t_{max}}}{\sum_{t_s=1}^{t_{s\,max}} m(t)_{cal}} . 100(\%)$$

Where $m(t)_{cal}$ is the total amount of NH_3 theoretically calculated until a time step t_s, $m(k)_{gen}^{t_s}$ is the amount of calculated NH_3 in each cell within the region between the injection hole and the monolith entrance at a time step t_s.

It is desirable that UWS be converted into NH_3 as much as possible within the distance between UWS injection nozzle and SCR catalyst entrancesince more generated ammonia leads to higher NO_x reduction efficiency.

Uniformity Index (UI)

It is important that the produced active substance is equally distributed over SCR catalyst entrance in order to use catalyst effectively. In case of ammonia evenly distributed over the surface, UI reaches 1 which means the flow is well mixed with ammonia and it has the following formula:

$$UI(\%) = 1 - \frac{\sum |\emptyset_{NH_3,i} - \overline{\emptyset}_{NH_3}| A_i}{2|\emptyset_{NH_3,i}| \sum A_i}$$

where$\emptyset_{NH_3,i}$is local value of mass fraction of ammonia at the face center of a sample center upstream of the catalyst ,$\overline{\emptyset}_{NH_3}$: Average value of ammonia mass fraction over the sampling surface, A_i: Cell area

2.3 Injection characteristics

2.3.1 Droplet size (SMD):A common way to describe the droplet size distribution is Sauter mean diameter (SMD) which is defined as the ratio between the mean droplet volume and the mean droplet surface area [7].The effect of droplet sizeon urea conversion efficiency and uniformity index is investigated at three different values namely 20-30 and 44 micron.

2.3.2 Injection velocity: The effect of injection velocity on evaluation parameters is researched at velocities of values 20-30 and 40 m/s.

2.3.3 Spray angle: The effect of spray angle on evaluation parameters considered is investigated at four different values namely 20^o-40^o-60^o and 70^o. Figure 3 shows a schematic view of spray angle from injector

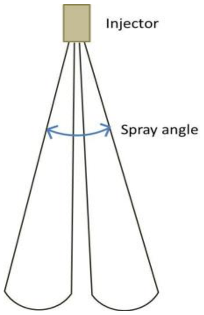


Fig. 3: Schematic view of spray angle from injector

The effect of these four injection characteristics on evaluation parameters is measured and estimated at SCR entrance at different exhaust flow velocities.Figure 4 and figure 5 demonstrate mass fraction of $NH_3$for initial injection conditions at different cross sections along the exhaust pipe and SCR converter.

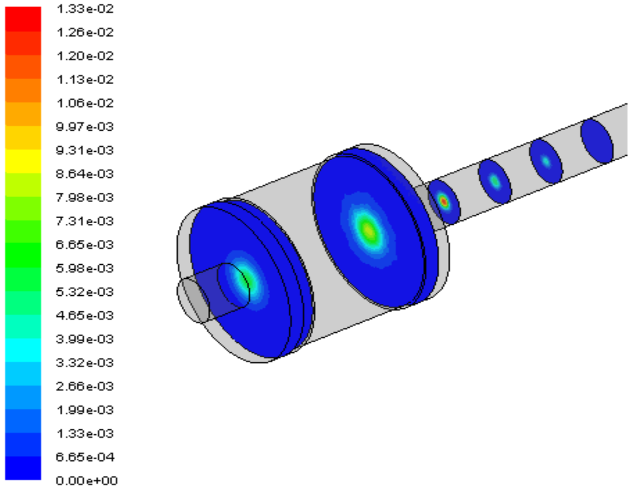


Fig.4: Contours of mass fraction of NH_3at 8.3 m/s

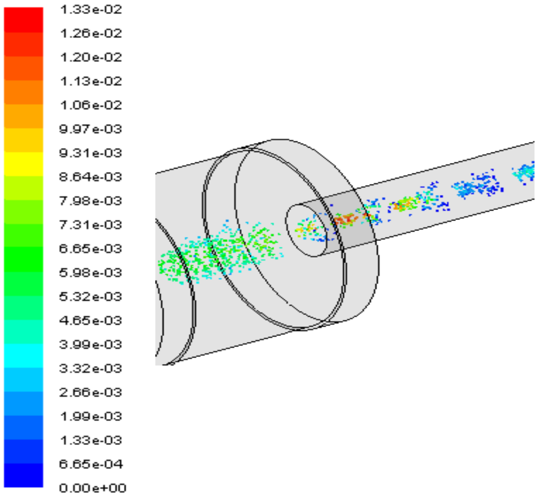


Fig. 5: Particle traces colored by mass fraction of NH_3at8.3 m/s

3. Results and Discussion

3.1 Effect of droplet size(SMD)

As evident from figure 6, urea conversion efficiency increases as SMD reduces from 44 to 20 micron. At a relatively small droplet size, spray dispersibility increases which reduce evaporation time and enhance thermolysis. The smaller the droplets are, the shorter the required vaporization time and the better the distribution in the flow. At reduced exhaust flow velocities, Ureaconversion efficiency is observed to increase because more residence time leads to better evaporation and higher ammonia generation. It provides large area of contact between the UWS drops and hot exhaust gas resulting in efficient chemical reaction between ammonia and NO_x.
The increased ammonia conversion leads to higher NO_x reduction efficiency. UI is observed to reduce along with urea conversion efficiency as SMD increases. Ithas the maximum value at 20 micron and starts to get reduce after this value as displayed in figure 7. UI increases with reduction of exhaust flow velocity because promoted mixing provide the chance for better flow distribution.

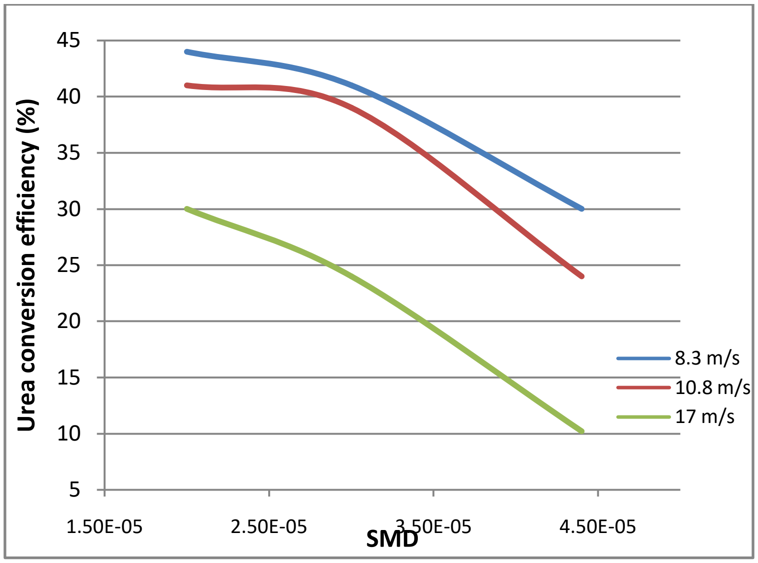


Fig.6: Effect of SMD on urea conversion efficiency at different velocities

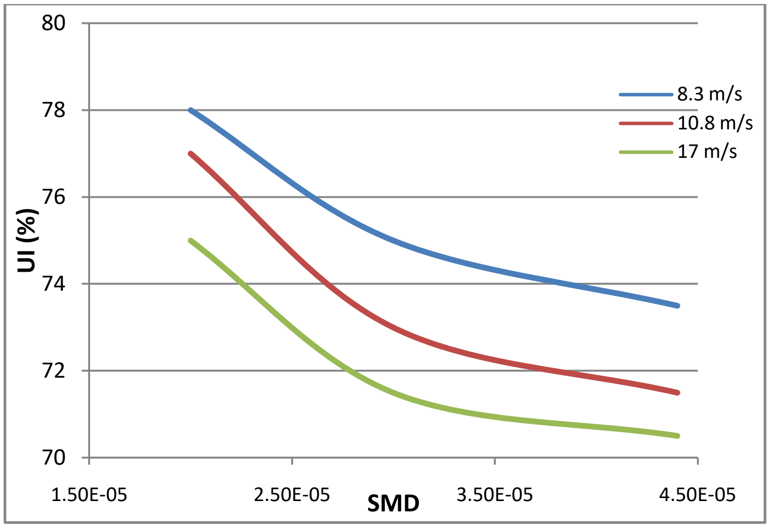


Fig.7: Effect of SMD on UI at different velocities

3.2 Effect of injection velocity

It can be concluded from figure 8 that urea conversion efficiency is increased with incrementof injection velocities. It reaches its maximum value atinjection velocity of 30 m/s and it gets inclinedat injection velocity of 40 m/s. By increasing the injection velocity, spray penetration length increases and the droplet size decreases which enhance the evaporation. However, very high injection velocities lead to less urea conversion efficiency due to incomplete evaporation because of decreased residence time and reduced inertial force.

UI increases up to 30 m/s andstartsreducing after this value as shown in figure 9. It gets enhanced at elevated exhaust flow velocities due to better mixing with exhaust gas.

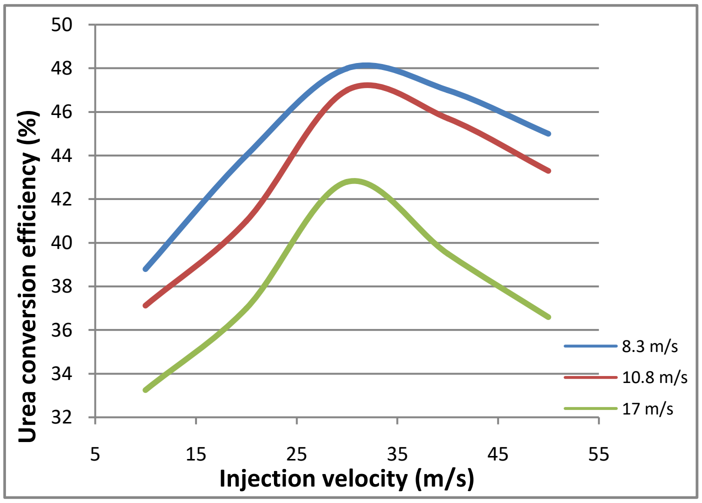


Fig. 8: Effect of injection velocity on urea conversion efficiency at different velocities

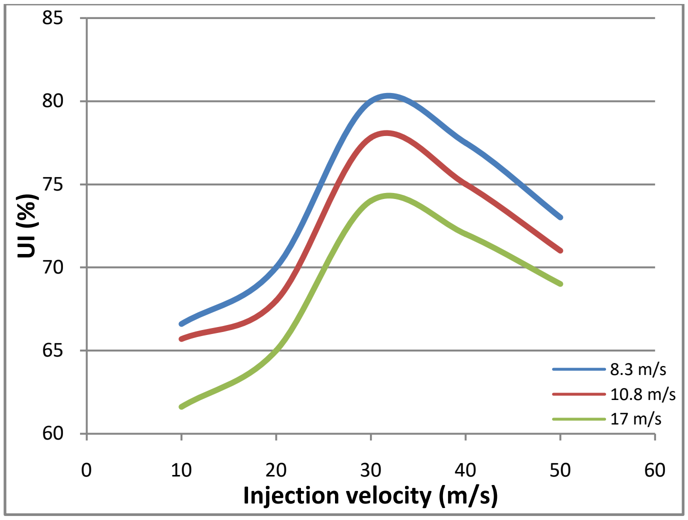
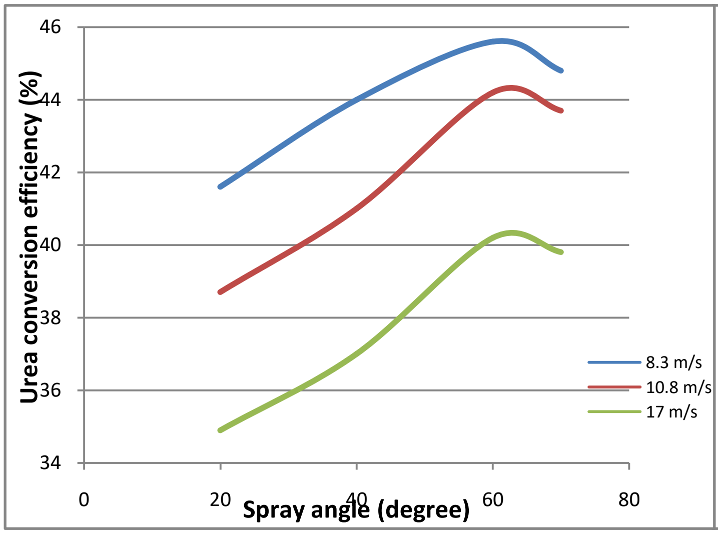


Fig.9: Effect of injection velocity on UI at different velocities

3.3 Effect of spray angle

As the injection angle increases, urea conversion efficiency and UI are observed to increase. Maximum values are obtained at 60 degree and they get reduced after this value as shown in figures 10and 11. At large injection angles, bigger radial space is occupied which results in better distribution of UWS with increased ammonia concentration. The radial distribution causes better mixing and increased residence time. However, too wide spray angle has a negative effect on the spray distribution because the relative velocity between the droplet and the surrounding gas becomes smaller leading to reduce the frictional drag force on the droplet and increase wall impingement.



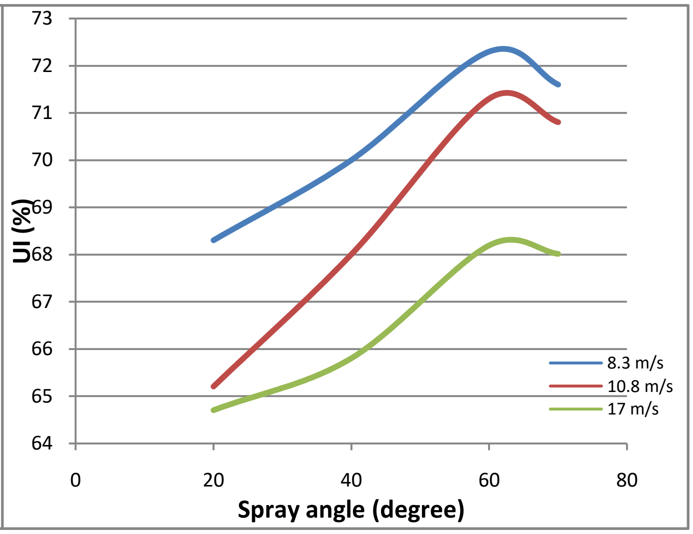
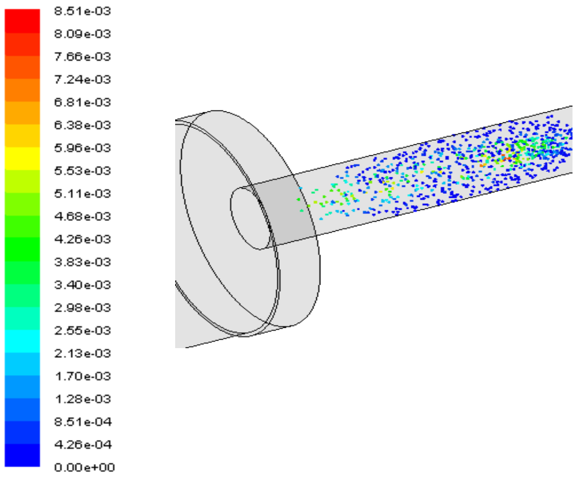


Fig.10: Effect of spray angle on urea conversion efficiency at different velocities

Fig.11: Effect of spray angle on UI at different velocities



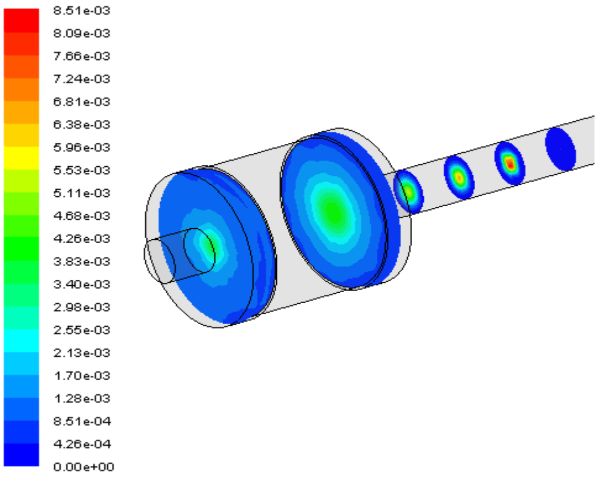


Fig.12: Particle traces of mass fraction of NH_3 at 8.3 m/sFig. 13: contours of mass fraction of NH_3 at 8.3 m/s

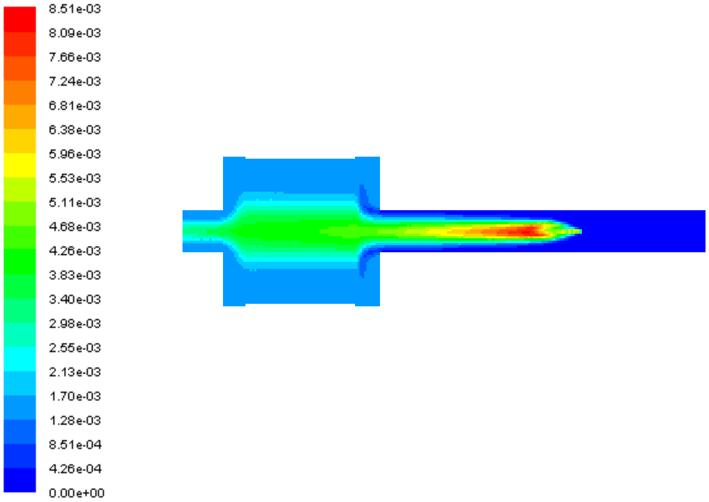


Fig.14:contours of mass fraction of NH_3 at 8.3 m/s

Based on numerical results obtained, the maximum urea conversion efficiency and UI are obtained at SMD of 20 micron, injection velocity of 30 m/s and spray angle of 60 degree. Comparing with base results, urea conversion efficiency after applying optimization parameters is 62.3% and UI is 83.5%. Hence, urea conversion efficiency is enhanced by 29.8% and UI enhanced by 4.37%. Figures 12, 13 and 14 show the improved results where higher ammonia is generated due to enhanced urea conversion efficiency and UI which automatically lead to promoted de-nitrification efficiency.

4. Conclusions and future perspectives

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 by injecting small-sized spray droplets, better urea conversion efficiency and UI are resulted. By increasing spray angle, better spatial distribution is achieved and more ammonia could be generated. On the other hand, too big spray angle will negatively affect the spray distribution due to wall impingement and reduced relative velocity between droplets and exhaust gas. High injection velocities lead to higher urea conversion efficiency and UI due to better UWS mixing with exhaust gas. However, very high injection velocities lead to less urea conversion efficiency due to incomplete evaporation because of decreased residence time and reduced inertial force.

In future studies, UI could be enhanced by adopting different types of static mixers downstream of UWS injector at specific positions so that mixing between droplets and exhaust gases is promoted which means better NO_x reduction.

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