

## Numerical analysis of NO<sub>x</sub> reduction for compact design in marine urea-SCR system

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**ABSTRACT:** In order to design a compact urea selective catalytic reduction system, numerical simulation was conducted by computational fluid dynamics tool. A swirl type static mixer and a mixing chamber were considered as mixing units in the system. It had great influence on flow characteristics and urea decomposition into ammonia. The mixer caused flow recirculation and high level of turbulence intensity, and the chamber increased residence time of urea-water-solution injected. Because of those effects, reaction rates of urea decomposition were enhanced in the region. When those mixing units were combined, it showed the maximum because the recirculation zone was significantly developed. NH<sub>3</sub> conversion was maximized in the zone due to widely distributed turbulence intensity and high value of uniformity index. It caused improvement of NO<sub>x</sub> reduction efficiency of the system. It was possible to reduce 55% length of the chamber and connecting pipe without decrease of NO<sub>x</sub> reduction efficiency.

**KEYWORDS:** Selective catalytic reduction; Urea decomposition; Uniformity index; NO<sub>x</sub> reduction; Compact design.

### INTRODUCTION

Nitrogen Oxides (NO<sub>x</sub>) emissions, which generally refer to Nitric Oxide (NO) and Nitrogen Dioxide (NO<sub>2</sub>), are produced by combustion processes in industry such as power generation boilers and internal-combustion engines. As is well known, it causes environmentally harmful effects by reacting with chemicals and organic compounds in the atmosphere. For that reason, its regulation has been getting strict. NO<sub>x</sub> emissions, especially from ships, have been regulated by the International Maritime Organization (IMO) (IMO, 2015a). As shown in Table 1 Tier III requires about 75% reduced NO<sub>x</sub> emissions compared to current Tier II level. It was supposed to be required to meet Tier III level from 2016 in Emission Control Areas (ECAs) which were defined in Appendix VII of Annex VI of MARPOL (IMO, 2015b). Selective Catalytic Reduction (SCR) system is one of technologies expected to meet such a regulation (Koebel et al., 2000). As contrasted with combustion techniques to control NO<sub>x</sub> emissions, SCR is an after-treatment system which has advantages such as high NO<sub>x</sub> reduction performance and low operating temperature (Turns, 2000). Urea Water Solution (UWS) is generally used as the reducing agent on the system because of toxicity and storage problems of gaseous ammonia (NH<sub>3</sub>). The conversion of UWS to NH<sub>3</sub> is dependent upon the ambient temperature and mixing (Koebel and Elsener, 1998). One of the problems to adopt the SCR system in the ship is limitation of

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space to install. Catalyst occupies large volume, and the adequate pipe length is necessary for mixing and evaporation of UWS injected. In order to improve mixing performance, it is required sufficient distance because of high velocity of exhaust gas because it is an important factor to affect the overall system performance. However, there are difficulties to evaluate mixing of gases with high velocity in the full-scale system. Hence, three dimensional computational fluid dynamics (CFD) methods are required to numerically simulate it.

In order to reduce required length for mixing, many researchers have studied about static mixers in pipe flow systems. Various factors to improve mixing and SCR performance have been investigated considering many types of mixer (Thakur et al., 2003; Chen and Williams, 2005; Regner et al., 2006; Zhang and Romzek, 2007; Zheng et al., 2009; Zheng et al., 2010; Park et al., 2014). However, a mixer for fluid mixing in the pipe was invented in the previous study (Choi et al., 2013). An advantage of this mixer is variability of vane angle. The correlation between flow mixing characteristics and pressure drop with the mixer were investigated (Park et al., 2014). These works were focused on the mixing in two different fluids. The SCR technique has been studied concerning chemical reactions. Kim et al. performed both experimental and numerical works on urea decomposition under various inlet velocity (Kim et al., 2004). They derived coefficients in Arrhenius equation for urea decomposition by means of a wet solid combusting particle model. Birkhold et al. modeled and analyzed the liquid-liquid and liquid-solid interactions with UWS (Birkhold et al., 2006; 2007). They also derived the Arrhenius coefficients using a multi-component particle model assuming that the mixture is homogeneous. Detailed chemistry and its kinetic model were developed in the recent studies (Ebrahimiyan et al., 2012; Brack et al., 2014). There have been also attempts to evaluate whole SCR system. Samuelsson et al. conducted a CFD study of mixing and droplet breakup concerning urea and NO<sub>x</sub> conversion, but their chemical model were not validated (Samuelsson and Holmberg, 2013). Choi et al. (2015) also carried out a numerical simulation of urea decomposition in the system. They discussed the correlation between turbulence intensity and UWS droplet location, but NO<sub>x</sub> reduction was not included.

There are not many researches considering de-NO<sub>x</sub> reactions in the whole SCR system under practical marine engine operating conditions even though effects of mixing and chemical reactions were individually conducted. Compactness of the system, especially, has not been studied. Therefore, the purpose of this numerical study is to evaluate the effect of mixing units on mixing characteristics between exhaust gas and urea water solution, to predict an overall performance of SCR system with a static mixer and a mixing chamber, and to propose parameters for compact design.

Table 1 MARPOL Annex VI NO<sub>x</sub> limits (IMO, 2015a).

Tier	Ship construction date on or after	Total weighted cycle emission limit (g/kWh) n: Engine's rated speed (rpm)		
		n<130	n=130-1999	n≥2000
I	1 January 2000	17.0	45·n <sup>(-0.2)</sup>	9.8
II	1 January 2011	14.4	44·n <sup>(-0.23)</sup>	7.7
III	1 January 2016	3.4	9·n <sup>(-0.2)</sup>	2.0

## NUMERICAL METHODS

### Geometry

Geometry of the SCR system and locations of each component are shown in Fig. 1(a). The mixer is installed at upstream of a mixing chamber. The chamber and reactor are connected with a pipe which has the same diameter with the exhaust pipe. Catalyst filter is located in the reactor.

Mixing species is of importance to obtain a desired reaction (Andersson et al., 2011). In the previous study, the swirl type mixer was invented for this system (Choi et al., 2013). It is shown in Fig. 1(b). It is divided into four parts by diagonal lines to generate swirl flow combining all parts, and each vane can be varied the angle. It was studied for effects of various angles and showed the best performance in the range of 30° to 60° concerning pressure drop (Park et al., 2014; Kim, 2013). In this study,

the case of angle of  $45^\circ$  was adopted and investigated the effects of flow mixing. A chamber was installed for mixing droplets with flow and generally increasing its residence time. Residence time is one of important factors to improve the system performance. Mixing chamber was considered to increase the residence time as well as mixing performance with its wider cross sectional area. It can improve the performance of system combining with the mixer. Design guidelines are needed for this chamber since it lengthens whole system. It occasionally causes modification of design of exhaust system. Therefore, it was investigated the effects of the length of chamber and connecting pipe.

The computational grid was generated by Gambit 2.4.6. It was mainly composed of hexahedral mesh, however, tetrahedral mesh was used in adjacent cells to the mixer because of its complex geometry. Four types of geometry were selected to simulate the system in terms of installing mixing units as listed in Table 2. Injection point was fixed at the same position in order to compare effects of mixing units.

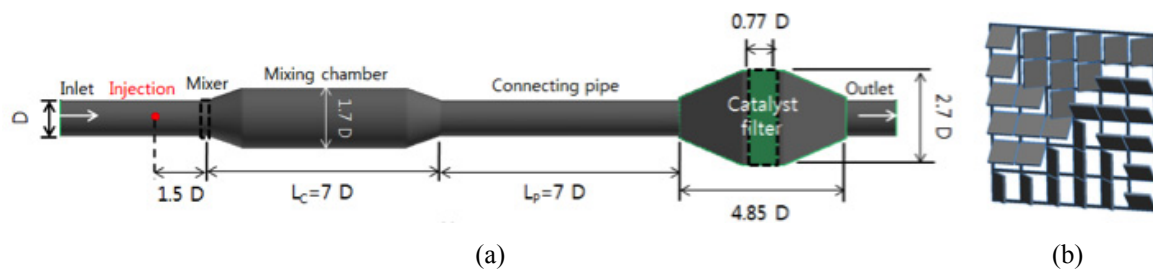


Fig. 1 Schematic diagram; (a) Geometry of the SCR system, (b) swirl type static mixer.

Table 2 Classification of computational domain.

Case No.	Mixer	Mixing chamber
1	X	X
2	O	X
3	X	O
4	O	O

### Numerical procedure

In order to predict performance of SCR system, it was investigated using a commercial three-dimensional CFD tool, ANSYS FLUENT. Practical operating conditions of ship engine were applied to the simulation. Four types of engine loads were applied to each case as listed in Table 3. Exhaust gas was composed of 72%  $N_2$ , 12%  $O_2$ , 10%  $H_2O$ , and 6%  $CO$ . It was calculated by two-equation turbulence model, realizable k- $\epsilon$ , assuming steady state. Wall boundary was considered as an adiabatic condition. Porous media was used for catalyst filter so that pressure drop occurs. Initial value of mean droplet diameter was assumed because of insufficient information of the nozzle under the practical engine operating conditions.

Table 3 Classification of engine loads and initial value of mean droplet diameter.

Engine load (%)	Average velocity (m/s)	Exhaust gas temperature (K)	Mean droplet diameter ( $\mu m$ )
25	11.50	612.45	52.8
50	20.51	602.85	39.6
75	27.84	592.15	22.0
100	36.05	585.95	13.2

### Porous media assumption

Catalyst filter is a core of the SCR system. It gives rise to most de-NO<sub>x</sub> reactions. In this study, a honeycomb type catalyst coated with Cu-ZSM-5 was adopted, and its cell density was 100 *psi*. In order to reduce computational costs, it is usually assumed as porous media. Pressure drop,  $\Delta p$ , can be calculated by an Eq. (1) over the specified volume.

$$\Delta p = -\left(\frac{\mu}{\alpha}v + C_2 \frac{1}{2}\rho v^2\right)\Delta m \quad (1)$$

where  $\alpha$  is the permeability and  $C_2$  is the inertial resistance factor. Pressure drop was measured to identify the constants under the various conditions of velocity. Viscous resistance factor,  $1/\alpha$ , and  $C_2$  were determined as  $1.1237 \times 10^7 \text{ l/m}^2$  and  $3.718 \text{ l/m}$ , respectively. Comparison of simulation and experiment was depicted in Fig. 2. The experimental data were provided by Hyundai Materials Co., Ltd.

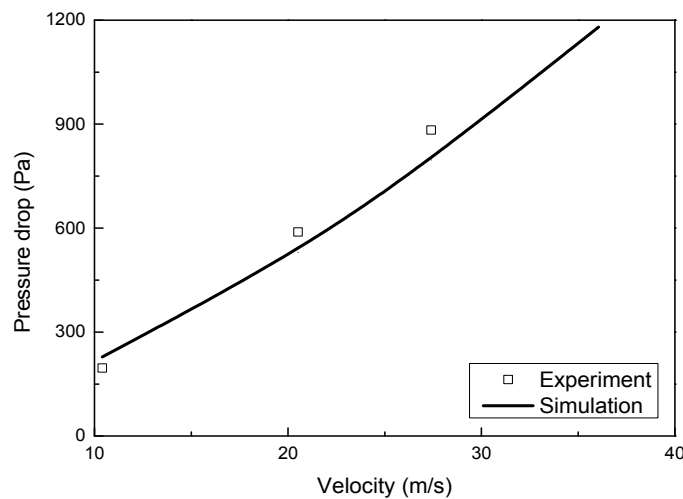


Fig. 2 Simulation results of pressure drop compared to experimental data.

### Atomizer and breakup

It is necessary to model atomizer in order to predict spatial distribution of droplets. Solid cone type spray nozzle was adopted to simulate a dosing unit. Injection angle and velocity were  $70^\circ$  and  $10.6 \text{ m/s}$ , respectively. Rosin-Rammler distribution was applied for droplet size distribution of injected UWS. It was determined as (Lefebvre, 1988):

$$1 - Q = \exp\left[-\left(\frac{D}{x}\right)^d\right] \quad (2)$$

where  $Q$  is the total volume fraction contained in droplets of diameter less than  $D$ .  $X$  is mean droplet diameter, and  $d$  is a measure of the spread of droplet sizes. Those values were given in the previous study, where  $X$  and  $d$  were  $44 \mu\text{m}$  and  $3.27$ , respectively (Kim et al., 2004).

Droplet breakup can be divided into two processes: primary and secondary breakup. Primary breakup is defined from characteristics of a nozzle, and liquid jet or sheet shattered into droplets. It determines initial size of droplets. Secondary breakup makes the droplets finer depending upon ambient gas conditions. Primary breakup was not included in this study, however, initial droplet diameter was assumed because of insufficient information of the nozzle, which is listed in Table 3. It was determined by calculation of NO<sub>x</sub> reduction efficiency with respect to UWS injection ratio comparing with the experimental data.

Taylor Analogy Breakup (TAB) model was used for droplet breakup. This model is based on an analogy between an oscillating and distorting droplet and a spring-mass system was used to simulate breakup phenomena. The restoring force of the spring, the external force on the mass, and the damping force are analogous to the droplet surface tension force, the gas aerodynamic force, and the droplet viscous force, respectively (O'Rourke and Amsden, 1987). In order to determine droplet drag coefficient, Dynamic drag model in ANSYS FLUENT was used. In cases of a spherical and distorted droplet the drag coefficient is determined as follows (FLUENT, 2011):

$$C_{d,sphere} = \begin{cases} 0.424 & \text{Re} > 1000 \\ \frac{24}{\text{Re}} \left(1 + \frac{1}{6} \text{Re}^{2/3}\right) & \text{Re} < 1000 \end{cases} \quad (3)$$

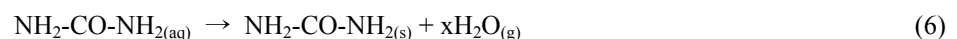
$$C_{d,distorted} = C_{d,sphere} (1 + 2.632y) \quad (4)$$

where  $y$  is the droplet distortion determined as follow:

$$\frac{d^2y}{dt^2} = \frac{C_F}{C_b} \frac{\rho g}{\rho l} \frac{y^2}{r^2} - \frac{C_k \sigma}{\rho l r^2} y - \frac{C_d u_l d_y}{\rho l r^2 dt} \quad (5)$$

### Urea decomposition

UWS, which is composed of 40% urea and 60% water, is injected into the exhaust pipe as reducing agent. 1 mol of urea can generate 2 mol of ammonia by evaporation, thermolysis and hydrolysis. After it is injected in the pipe, hot exhaust gas evaporates water in the solution, and urea is existed in the form of solid or molten phase. Then it decomposes thermally and generates isocyanic acid and ammonia. Isocyanic acid is easily hydrolyzed with water vapor though it is stable in gas phase. Equilibrium chemical reactions are expressed as following equations (Koebel et al., 2000):



Yim et al. (2004) investigated the decomposition of urea into ammonia over the Cu-ZSM-5 catalyst and provided a kinetic model for thermal and catalytic decomposition of urea (Baik et al., 2006). Kim et al. (2004) carried out experimental research to find out ammonia conversion efficiency at various temperature and gas velocity ranges which were relevant to operating conditions of a practical marine diesel engine. In this study, thermal and catalytic urea decomposition adopted the kinetic models which were adjusted marine engine conditions as shown in Table 4. Thermal and catalytic urea decomposition took place in the pipe and on the catalyst, respectively. It was validated the previous experimental result as shown in Fig. 3. Here,  $\text{NH}_3$  conversion efficiency was defined as below in order to evaluate the degree of urea decomposition.

$$\text{NH}_3 \text{ conversion efficiency} = \frac{\text{Amount of NH}_3 \text{ generated}}{\text{Amount of NH}_3 \text{ when urea completely decomposes}} \times 100 \quad (9)$$

Table 4 Arrhenius constants of thermal and catalytic urea decomposition.

Reaction	Thermal decomposition		Catalytic decomposition	
	Pre-exponential factor	Activation energy (J/kgmol)	Pre-exponential factor	Activation energy (J/kgmol)
$\text{NH}_2\text{-CO-NH}_{2(s)} \rightarrow \text{NH}_{3(g)} + \text{HNCO}_{(g)}$	$4.9 \times 10^3$	$2.3 \times 10^7$	$4.5 \times 10^3$	$2.26 \times 10^7$
$\text{HNCO}_{(g)} + \text{H}_2\text{O}_{(g)} \rightarrow \text{NH}_{3(g)} + \text{CO}_{2(g)}$	$2.5 \times 10^5$	$6.22 \times 10^7$	$3.1 \times 10^4$	$1.58 \times 10^7$

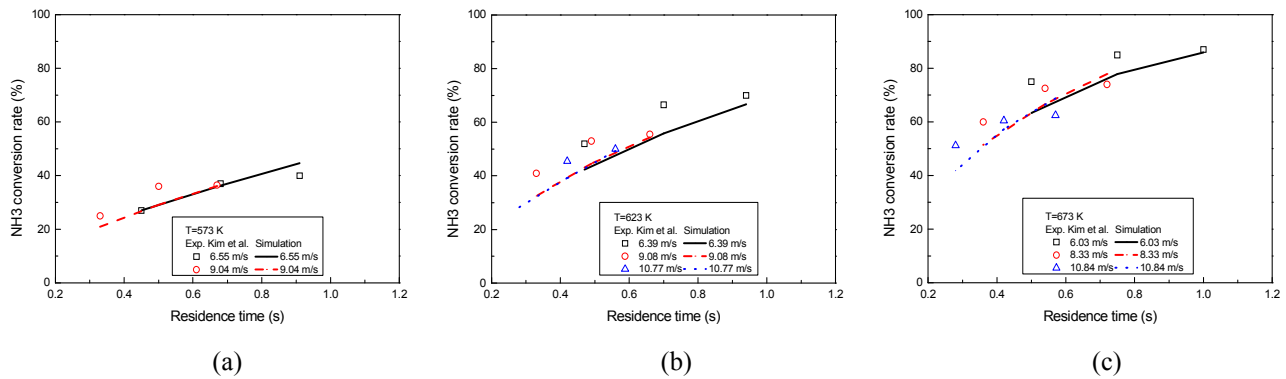


Fig. 3 Simulation results of decomposition urea into NH<sub>3</sub> under various temperature compared to experimental data; (a) 573 K, (b) 623 K (c) 673 K.

**NO<sub>x</sub> reduction**

In order to predict the de-NO<sub>x</sub> performance of SCR systems, three main reactions were considered. It can be briefly represented as follows (Koebel et al., 2000):



In the SCR system NH<sub>3</sub> mainly reacts with NO since NO<sub>x</sub> emissions from diesel engine mostly composed of NO, generally more than 90%. Hence, Eq. (10) is the main reaction. Eq. (11) is much faster and Eq. (12) is slower than Eq. (10). The reactions are typically described as Arrhenius equation. Table 5 represented pre-exponential factors and activation energies (Olsson et al., 2008).

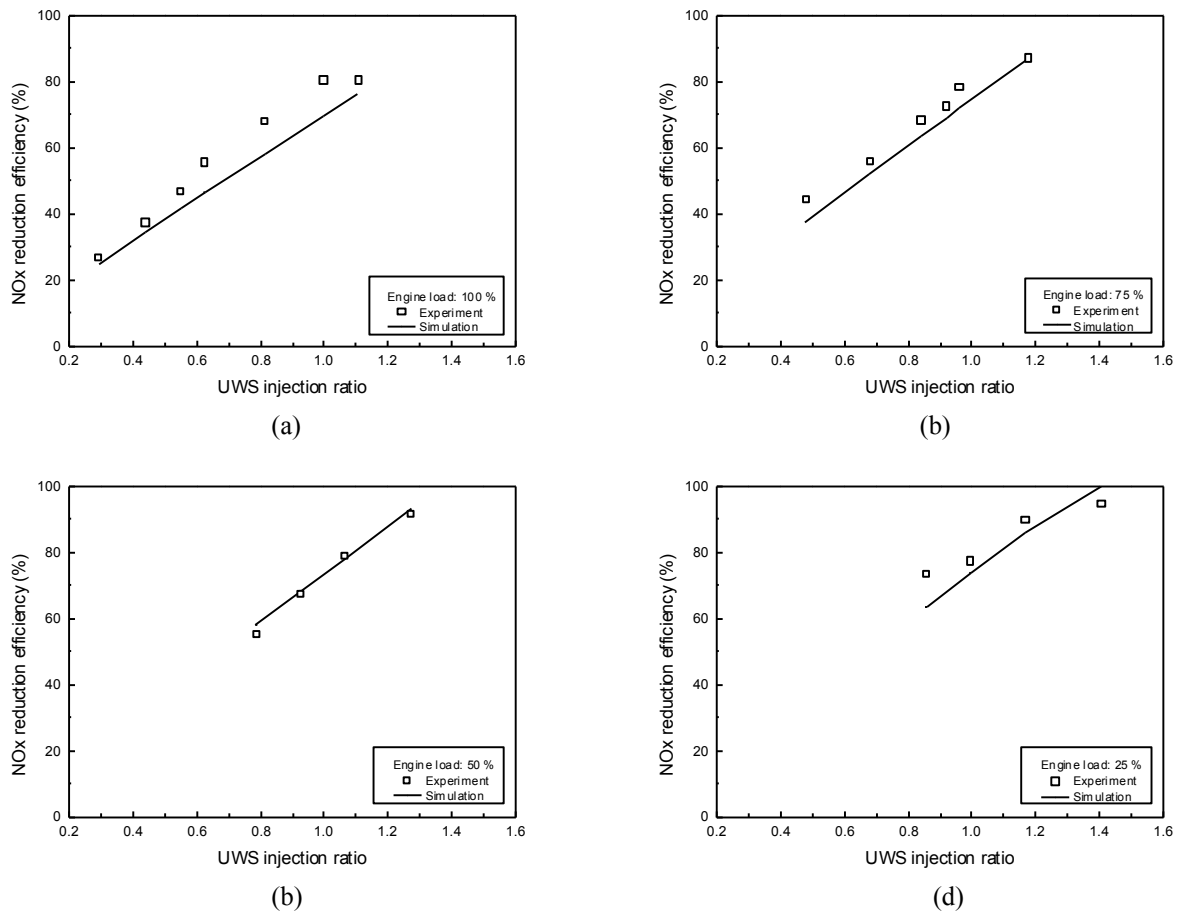
In this study, it was assumed that de-NO<sub>x</sub> reactions were occurred only over the catalyst. The kinetic models were validated with experimental data, which were provided from Hyundai Materials Co., Ltd with geometry of case 3, and the results are shown in Fig. 4. It was evaluated with various UWS injection ratio. Here, ratio which was defined as follow.

$$\text{UWS injection ratio} = \frac{\text{Actual injection rate of UWS}}{\text{Stoichiometric injection rate of UWS}} \tag{13}$$

If the ratio has a value of 1, it could completely remove NO<sub>x</sub> emissions when the urea decomposition and de-NO<sub>x</sub> reactions occur ideally.

Table 5 Arrhenius constants of NO<sub>x</sub> reduction reactions (Olsson et al., 2008).

Equation	Pre-exponential factor	Activation energy (kJ/mol)
$4\text{NH}_3 + 4\text{NO} + \text{O}_2 \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O}$	$2.3 \times 10^8$	84.9
$2\text{NH}_3 + \text{NO} + \text{NO}_2 \rightarrow 2\text{N}_2 + 3\text{H}_2\text{O}$	$1.9 \times 10^{12}$	85.1
$4\text{NH}_3 + 3\text{NO}_2 \rightarrow 3.5\text{N}_2 + 6\text{H}_2\text{O}$	$1.1 \times 10^7$	72.3

Fig. 4 Simulation results of NO<sub>x</sub> reduction under various engine load compared to experimental data; (a) 100%, (b) 75%, (c) 50%, (d) 25%.

## RESULTS AND DISCUSSION

### Flow characteristics

Static mixer significantly affected velocity field as shown in Fig. 5(a). It was observed that velocity decreased by the mixing chamber in cases 2 and 3, and a recirculation zone was located in the center of pipe in cases 2 and 4. Especially, in case 4, the recirculation zone was more developed with the combination of the mixer and chamber. It was generated by the swirling flow induced by the mixer since the flow dispersed from center to wall.

It was observed that residence time of UWS droplets was increased regardless of the type of mixing units as shown in Fig. 5(b). However, the way of time increase was different. Droplet path length was extended by swirling flow and the recirculation zone in case of using the mixer. On the other hand, the residence time was increased by velocity decline in case of using the chamber. When the mixing units were combined, it was observed that the residence time was significantly increased due to wide range of the recirculation zone.

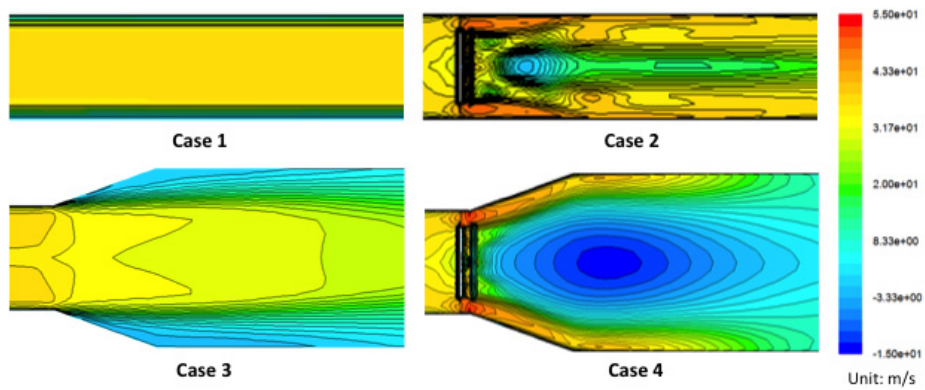
Velocity variance generated by passing through the mixing units intensifies turbulence, and it generally brings about better mixing. Turbulence Intensity (TI) was defined as follow:

$$TI = \frac{u'}{\bar{U}} \tag{14}$$

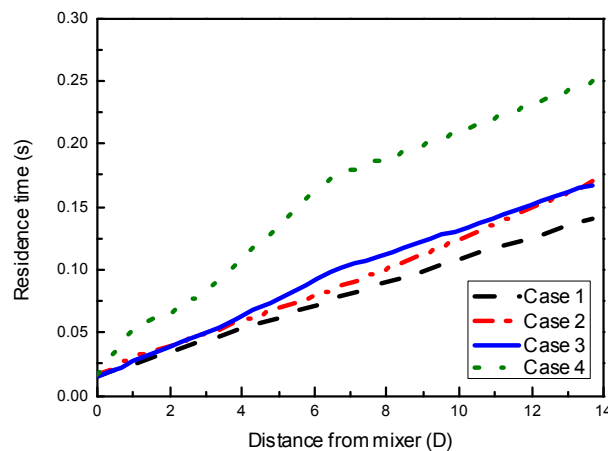
where  $u'$  is fluctuating velocity and  $\bar{U}$  is average velocity. Contours of TI were represented in Fig. 6(a). It was observed that high value of TI was achieved and stretched in case 2 whereas it was gradually increased by the chamber in case 3. In particular, case 4 showed the highest value of TI in the wide range of the forepart of the chamber. The swirling flow of the mixer produced a higher level of TI compared to the diffusing flow of the chamber. In addition, the mixing chamber enhanced the effect of the mixer in terms of TI.

Turbulence generation and dissipation can be briefly described by the trends of TI along streamwise axis as shown in Fig. 6(b). It was calculated by averaging values at each cross section. It was observed that the high level of TI peak was taken place in a short distance from the mixer in cases 2 and 4. Further, TI peak of case 4 showed the highest value and the closest to the mixer by means of the combination of the mixer and the chamber. It can be concluded that turbulence was intensified by the mixer, and it was more developed by using the mixing chamber.

On the contrary, a large peak was obtained at the end of the chamber in case 3 although there was a small peak in case 4. The sharp TI peak in case 3 was produced by the center-concentrated flow which caused by flow disturbance, whereas the small peak in case 4 came from swirling flow which can smoothly pass the end of the chamber along the wall side.



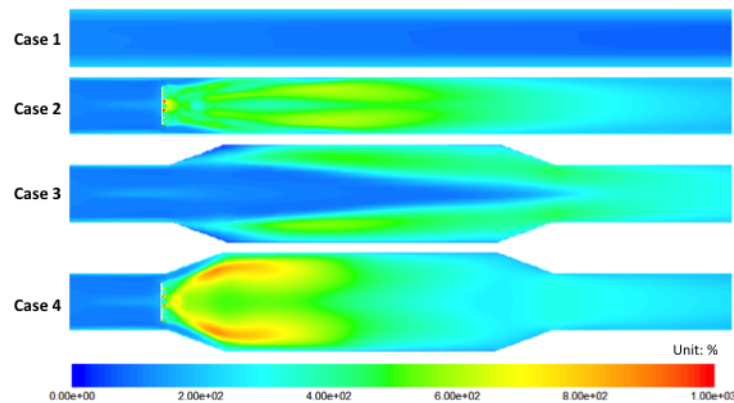
(a)



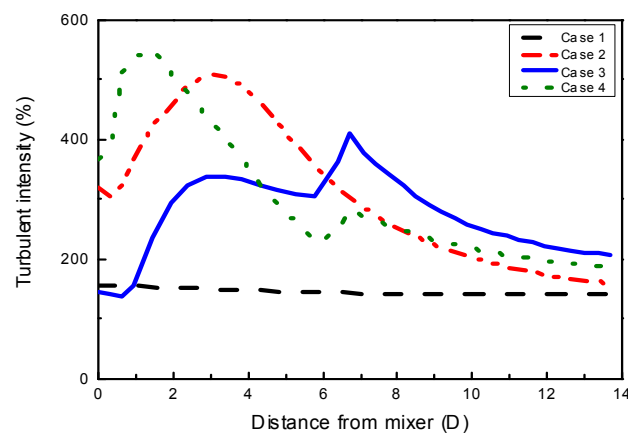
(b)

Fig. 5 Effects of mixing units under engine load of 100%; (a) contours of velocity, (b) droplet residence time.





(a)



(b)

Fig. 6 TI under engine load of 100%; (a) contours of TI, (b) averaged TI from mixer.

### Reaction rates of urea decomposition

Urea thermally decomposes in the hot exhaust gas stream. After evaporation of water, two steps of decomposition were expressed in Eqs. (7) and (8), which represent thermolysis and hydrolysis, respectively. Reaction rate is a degree how fast the reaction takes place. It can be a factor to measure length for mixing required.

Contours of the reaction rate of thermolysis are represented in Fig. 7(a). Thermolysis took place almost simultaneously with UWS injection. A local reaction area was observed with different mixing units. It was center-concentrated in cases 1 and 3. It showed the similar reaction area regardless of the mixing chamber, where it followed the velocity distribution. UWS droplets could not be distributed to the radial direction without the mixer. Locating droplets on the high TI area is an important factor to increase urea decomposition (Choi et al., 2015). Thus, the reaction was limited at the pipe center despite TI increased as it flows in the chamber. A widely spread reaction area of thermolysis was observed in cases 2 and 4. The extent of the local area decreased due to the mixer. As discussed in the previous section, TI dramatically increased with the result of flow induced by the mixer. TI showed a high value at the downstream of the mixer, and it completely covered inside of the exhaust pipe. In consequence, thermolysis can take place in whole area of the pipe. In the recirculation zone, however, a different reaction phenomenon was observed. Thermolysis was most activated at the inside of the recirculation zone in case 2, whereas it was at the forepart of the recirculation zone in case 4. Thermolysis can be easily taken place due to the TI peak of case 4, which was higher and closer to the mixer than that of case 2.

The other process of urea decomposition is hydrolysis. Contours of the reaction rate of hydrolysis are represented in Fig. 7(b). It can be seen that the contours have a similar trend compared to Fig. 7(a) although it is shifted to downstream. The shift was obvious because thermolysis and hydrolysis took place in sequence. The reaction rates were center-concentrated in cases 1 and 3, and widely distributed in cases 2 and 4. Especially in case 3 the local reaction area appeared at the rear of the chamber,

and disappeared after flowing out of it. It can be concluded that TI is a factor to have directly influence on hydrolysis as well as thermolysis considering that the highest value of TI was observed at the point.

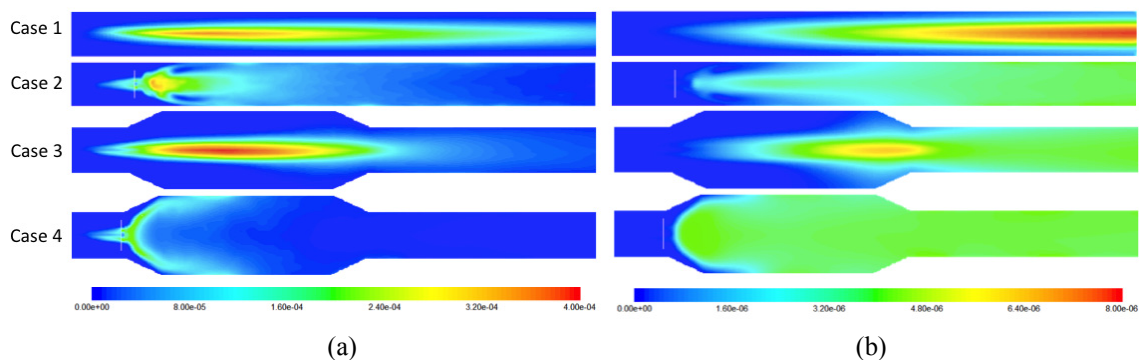


Fig. 7 Contours of reaction rate of urea decomposition; (a) thermolysis, (b) hydrolysis.

### NH<sub>3</sub> conversion efficiency and uniformity index

NH<sub>3</sub> gas generated by urea decomposition reduces NO<sub>x</sub> emission in the SCR system. One of the critical factors to predict NO<sub>x</sub> removal performance is a conversion efficiency of urea into NH<sub>3</sub>. Fig. 8(a) represented NH<sub>3</sub> conversion efficiency along streamwise axis from the mixer. It can be seen that case 4 achieved superior NH<sub>3</sub> conversion to the other cases. Case 2 showed relatively low efficiency considering the results of reaction rates although it was expected to generate NH<sub>3</sub> as much as case 4. It was observed that the efficiency of case 3 was slightly lower than that of case 2 even though it was similar to that of case 1 at the beginning of the chamber. In other words, effects of the mixer on NH<sub>3</sub> conversion took place instantaneously. It had a great influence on the urea decomposition by recirculating the flow, inducing high TI, and distributing the droplets. Contrarily, the chamber required sufficient length to obtain effects. Nonetheless, it created a great synergy combining with the mixer. The widely developed recirculation zone increased the droplet residence time in case 4, which means that the time for reaction became longer.

However, NH<sub>3</sub> conversion efficiency was not always proportional to the residence time. When it flows out of the chamber, the residence time was still increasing in a certain rate, whereas the increasing rate of the efficiency was getting lower. In addition, the droplet residence time of case 3 was higher than that of case 2, which is a contrast to the result of NH<sub>3</sub> conversion efficiency. Thus, it is necessary for high NH<sub>3</sub> conversion efficiency to combine both mixing units so as to obtain maximal effects.

Uniformity index (UI) of NH<sub>3</sub> was considered to measure the degree of mixing. Especially, UI of NH<sub>3</sub> at inlet of SCR catalyst has direct influence to NO<sub>x</sub> reduction efficiency of the system (Song et al., 2014). UI of NH<sub>3</sub> along streamwise axis is shown in Fig. 8(b). As described in the previous section, instantaneous effects of the mixer were observed. In cases 2 and 4, UI of NH<sub>3</sub> was dramatically increased after the mixer. It showed excellent mixing performance with a value of more than 0.95 from the second half of the chamber, and the value was maintained as flowed to the downstream. It means that a compact system is feasible with the mixer. Further, a compacter system can be achieved using both mixing units considering NH<sub>3</sub> conversion efficiency. In contrast, low level of mixing performance was observed in case 3 although UI value of more than 0.95 achieved from the outlet of the chamber. In addition, NH<sub>3</sub> conversion efficiency was not as high as the other cases except case 1. It implies that sufficient length of the chamber is required for better mixing. Thus, it is not appropriate to shorten the length of the system without the mixer.

The effects of the mixing units on UI of NH<sub>3</sub> at inlet of the catalyst filter were represented in Fig. 8(c). It can be seen that a lower value of UI under the engine load of 100% compared to Fig. 8(b), because the exhaust gas was concentrated on the center of pipe because of the high velocity as the exhaust gas flowed into the SCR reactor. It caused that urea decomposition did not take place homogeneously over the cross sectional area. Further, it was observed that UI decreased gradually in all cases as the engine load increased because of velocity increase. As velocity of flow increased, the droplets could not be diffused as much as flow. In cases with the mixing units, it showed about 15% increase of UI in comparison with case 1. Cases 2 and 4 showed a similar level of UI, which was 1-2% higher than that of case 3. There were no significant differences in terms of UI at inlet of the catalyst. Therefore, NO<sub>x</sub> reduction efficiency can be mainly affected by NH<sub>3</sub> conversion efficiency.

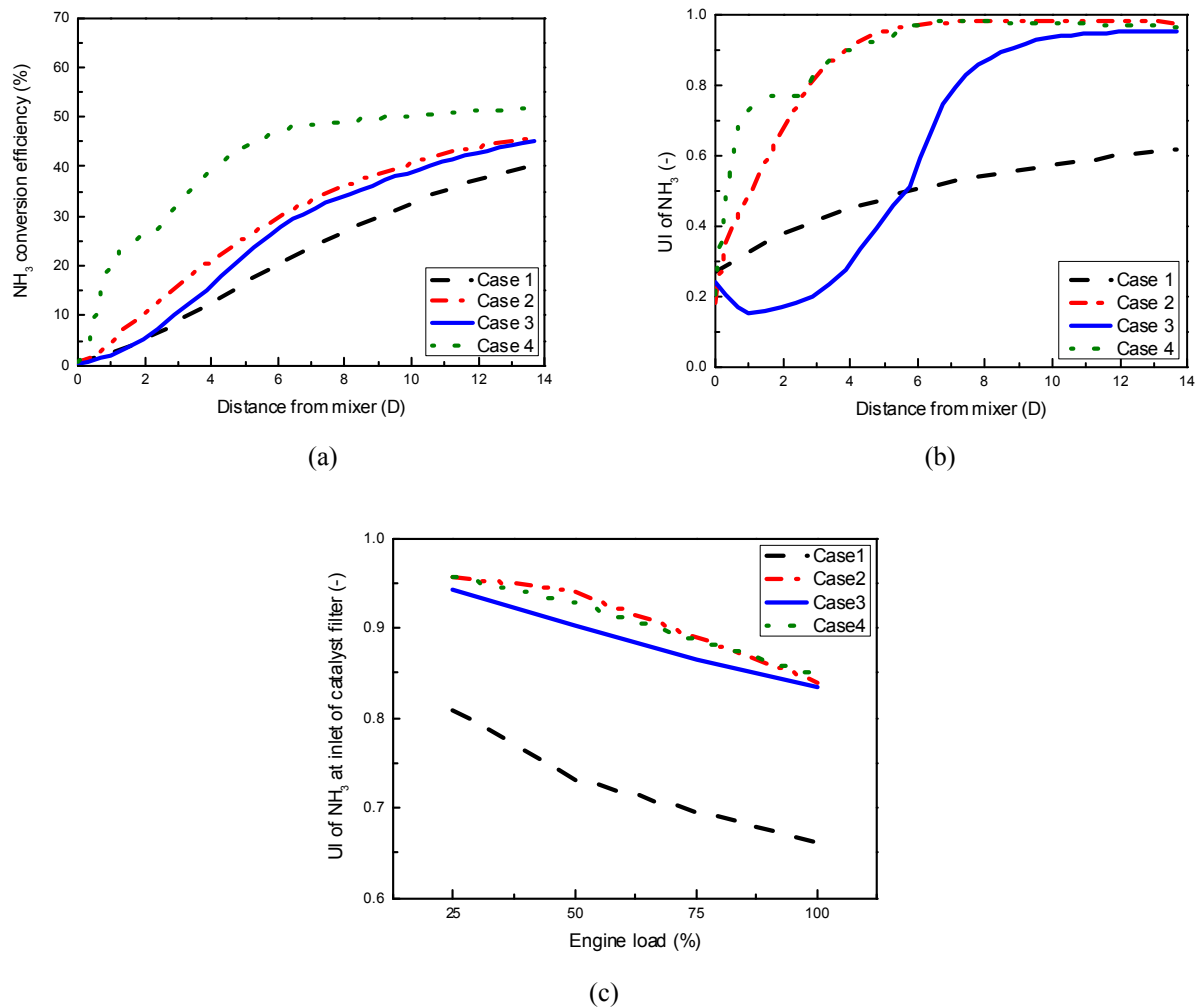


Fig. 8 (a) NH<sub>3</sub> conversion efficiency under the engine load of 100%, (b) UI of NH<sub>3</sub> concentration under the engine load of 100%, (c) UI of NH<sub>3</sub> concentration at inlet of catalyst filter

### NO<sub>x</sub> reduction efficiency

Main purpose of SCR system is to reduce NO<sub>x</sub> emission. In the previous sections, it was investigated major factors affect SCR performance. NO<sub>x</sub> reduction efficiency was achieved as shown in Fig. 9. It can be seen that there was no significant difference of NO<sub>x</sub> reduction efficiency under the engine load of 100%. The initial size of droplet caused by the primary breakup was assumed as listed in Table 3. The assumed size would be too small to predict exact value. Nonetheless, it showed the same tendencies of NO<sub>x</sub> reduction efficiency.

It can be seen that de-NO<sub>x</sub> performance was improved by installing mixing units compared to that of case 1. It showed that NO<sub>x</sub> reduction efficiency was increased up to 35% and averagely 17%. As reported, case 4 had outstanding results in terms of the major factors. Likewise, it showed the best NO<sub>x</sub> reduction efficiency under all engine loads. Although case 2 had a similar value of UI of NH<sub>3</sub>, it showed lower de-NO<sub>x</sub> efficiency because of comparatively low NH<sub>3</sub> conversion efficiency. In the same manner, case 3 had slightly lower performance than case 2. Further, similar to Fig. 8(c), overall NO<sub>x</sub> reduction efficiency decreased as the engine load increased. In order to improve NO<sub>x</sub> reduction efficiency and reduce usage of UWS, it was needed to decrease velocity of the exhaust gas. In cases 2 and 4, it was observed that NO<sub>x</sub> emission was reduced more than 90% at UWS injection rate of 1.1 under the engine load of 25%, however, it was less than 80% at the same injection rate under the engine load of 100%. Comparing case 2 and 4, differences of NO<sub>x</sub> reduction became larger as the engine load decreased. Therefore, it can be concluded that a compact SCR system can be achieved by using both mixing units without decrease of NO<sub>x</sub> reduction efficiency.

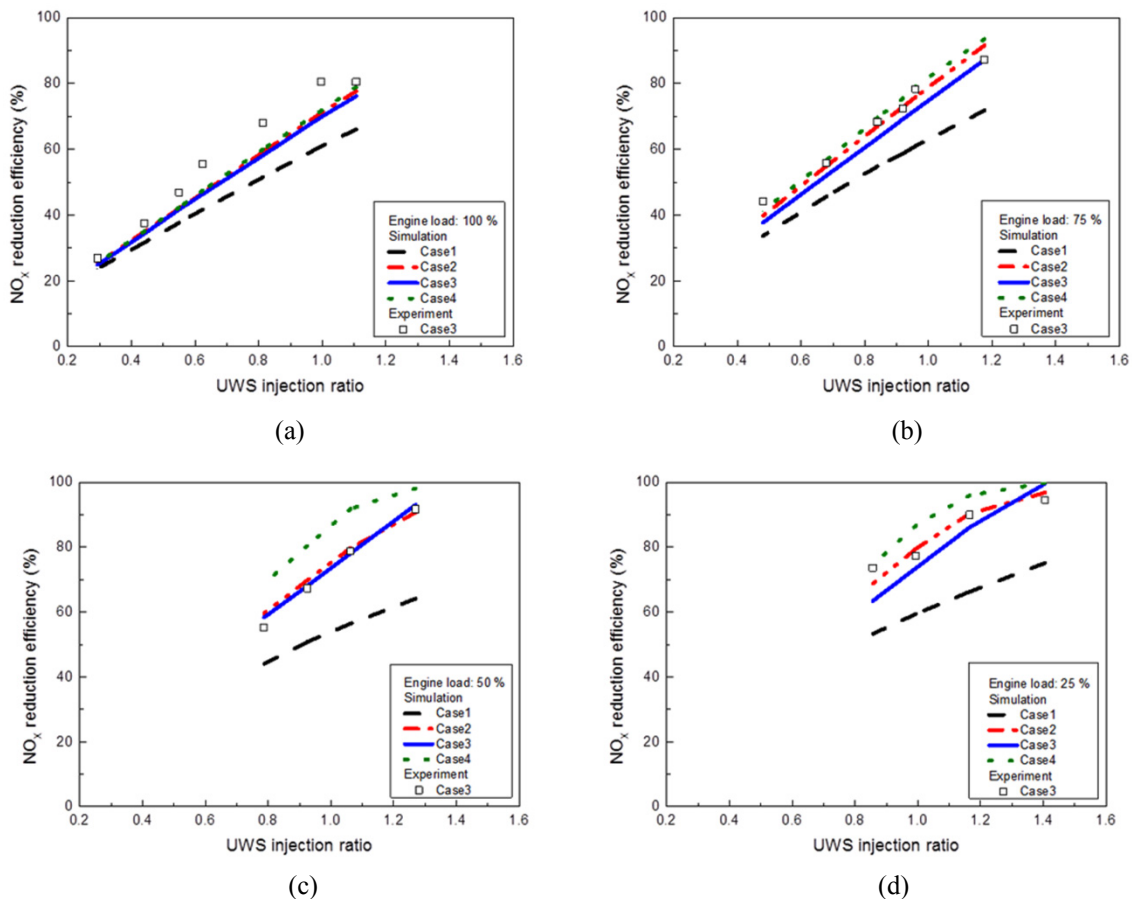


Fig. 9 Simulation results of NO<sub>x</sub> reduction efficiency under various engine loads; (a) 100%, (b) 75%, (c) 50%, (d) 25%.

**Design guidelines for compact SCR system**

To summarize the previous results, it was concluded that the compact system could be designed using both mixing units. At the beginning, the length of the chamber and the pipe was 7 D. Reducing the length of the chamber and the connecting pipe, NO<sub>x</sub> reduction efficiency was measured and compared with the simulation results in Fig. 4 which represented prediction of NO<sub>x</sub> reduction efficiency in the reference case. It was assumed that the design would be applicable if it showed a better NO<sub>x</sub> reduction efficiency than that of the reference case.

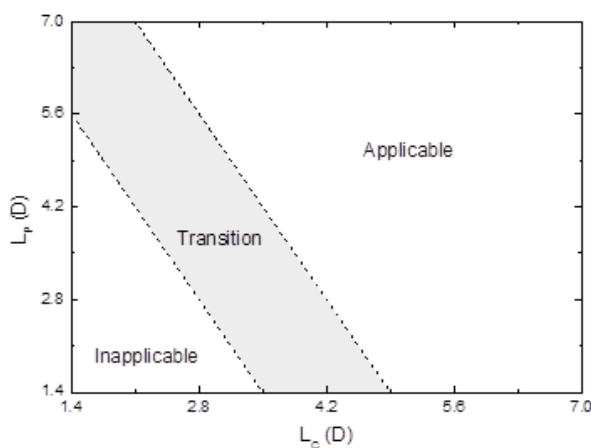


Fig. 10 Design guideline for SCR system in terms of length.

Range of the length for compact design was divided into three regions, applicable, transition, and inapplicable, as shown in Fig. 10. Transition implies that it depends on the engine operating condition if the system satisfies NO<sub>x</sub> reduction efficiency. If the chamber and the pipe are reduced independently, it would be obtained 20% and 30% reduced value, respectively. Another set of values can be chosen situationally in the applicable range even though reduction rate of total length would be increased. It was achieved that the minimum value was 55% reduced where the chamber and the pipe were reduced 30% and 80%, respectively.

## CONCLUSIONS

In this study, the effects of mixing units on mixing characteristics in marine selective catalytic reduction system was numerically investigated using ANSYS FLUENT in order to predict NO<sub>x</sub> reduction efficiency and to propose design guidelines for compact system.

- 1) The swirl type mixer and the mixing chamber were considered as the mixing units. In case of using the mixer, it induced intense turbulent flow and recirculation zone. It caused that UWS can be mixed in the short distance and the reaction rates of urea decomposition increased. However, NH<sub>3</sub> conversion efficiency was not relatively high because its effect was not maintained along downstream.
- 2) In case of using the mixing chamber, it showed good mixing performance. However, it was difficult to design a compact system due to the long distance to mix.
- 3) In case of using both mixing units, it showed the advantages of each device, which were the short distance to mix and maintaining good mixing performance.
- 4) The effect of length of the chamber and connecting pipe on NO<sub>x</sub> reduction efficiency was investigated to propose the design guidelines. It was possible to reduce about 55% of total length maintaining the NO<sub>x</sub> reduction efficiency.

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