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Tian, Xinna and Xiao, Youhong and Zhou, Peilin and Zhang, Wenping and Chu, Zhenhao and Zheng, Wei (2015) Study on the mixing performance of static mixers in selective catalytic reduction (SCR) systems. Journal of Marine Engineering & Technology, 4 (2). pp. 57-60. ISSN 2056-8487 , http://dx.doi.org/10.1080/20464177.2015.1096615

Study on the mixing performance of static mixers in SCR application

Xinna Tian[1,2], Youhong Xiao[1], Peilin Zhou[2], Wenping Zhang[1] ,Zhenhao Chu[1], Wei Zheng[1]

1. College of Power and Energy Engineering, Harbin Engineering University, Heilongjiang, China

2. Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, Scotland, UK

Corresponding author: Youhong Xiao Tel: +86 0451 82519199 Email: xiaoyouhong@hrbeu.edu.cn

SYNOPSIS

Selective catalytic reduction (SCR) system is a promising technique for reducing nitrogen oxides (NOx) emissions from diesel engines. Static mixers are widely used in SCR systems before reactors to promote the mixing between ammonia and exhaust streams. This work aims to investigate the effects of the location of static mixers and the volume ratio of two species on mixing quality by CFD method. Simulation results show that more homogenous ammonia distribution can be achieved at the exit of the pipe if static mixers are placed close to the ammonia injection point or more ammonia is injected. Another phenomenon found in the study is that the mixing performance of an identical static mixer may behave discrepantly under different flow conditions if using B and C as the evaluating indexes for mixing homogenisation.

AUTHORS' BIOGRAPHIES

Xinna Tian gained a BEng degree in Thermal Energy and Power Engineering from Harbin Engineering University in 2009. Now she is a PhD student in Marine Engineering at Harbin Engineering University. Her research interests are focused on removing NOx emissions from diesel engines by SCR technique, including SCR system design, control and optimisation. She is also pursuing a PhD degree at University of Strathclyde.

Youhong Xiao is a vice professor and master supervisor at Harbin Engineering University. He graduated from the department of Naval Architecture, Ocean and Marine Engineering of University of Strathclyde with a PhD degree. His research interests include control of vibration and noise of power equipment, noise source identification and NOx emission control of marine diesel engine.

Wenping Zhang graduated from Harbin Shipbuilding Engineering Institute with a BEng in the Department of Power Engineering in 1984, followed by an MSc and a PhD in 1984 and 1990 respectively. He has more than 25 years' experience in the control of noise, vibrations and exhaust gas emissions of power equipment.

Peilin Zhou is a professor of marine engineering in the Department of Naval Architecture, Ocean and Marine Engineering at University of Strathclyde. He obtained his BEng, MSc at Dalian Maritime University and a PhD at Newcastle University. His research interests include diesel engine combustion and efficiency enhancement, exhaust gas emissions control, alternative fuels and ship ballast water treatment.

INTRODUCTION

Selective catalytic reduction (SCR) is an effective technology to reduce nitrogen oxides (NOx) emissions from diesel engine.[1] The principle of this technology is the reduction of NOx in engines' exhaust by ammonia (NH_3) with the presence of catalysts above a temperature of 250 ˚C. Theoretically the reduction leads to innocuous nitrogen (N_2) and water (H_2O). However, the unreacted ammonia (ammonia slip) emitted to the atmosphere is also a noticeable problem as referred to in Björn's paper.[2] The volume ratio of ammonia to exhaust gas is usually much less than 1/100 in SCR application. It is difficult to mix these two species homogenously in such a small ratio under a limitation of mixing distance. The coefficient of variation (CoV) of ammonia before catalysts has a significant influence on SCR conversion efficiency and ammonia slip. By improving the homogenisation of ammonia distribution, SCR conversion efficiency can be advanced and ammonia slip can be reduced. Therefore, static mixers are commonly used before SCR reactors to enhance the mixing between ammonia and exhaust streams.

SCR manufacturers such as Haldor Topsøe, Tenneco, Bosch, MAN B&W, Wärtsilä, Mitsui, Hitachi, Daewoo and MTU have equipped static mixers on their SCR systems. These static mixers are either designed by SCR manufacturers themselves or introduced directly from the manufacturers of static mixers, such as Sulzer, Koch-Glitsch, Cheminner, Toray, FBE, Balcke Durr and ENVIRGY. The studies of static mixers are mainly concentrated on revealing mixing mechanisms, optimising the structures of static mixers and evaluating the performance of static mixers. Numerical simulations supported by experiments are effective ways to investigate the characteristics of static mixers. The characteristics concerned of static mixers may vary with the occasion of application. However the characteristics mostly considered are the heat transfer ability, pressure loss, flow uniformity and mixing homogenisation.

The mixing performance of an identical static mixer may behave dissimilarly under different flow conditions. This study introduces the indexes used for evaluating the mixing ability of static mixers and the factors which may affect the performance of static mixers. A commonly used GK static mixer unit is simulated by CFD software ANSYS Fluent in current research to investigate the effect of the location of static mixers and the volume ratio of two species on mixing quality.

SIMULATION MODELING

The case engine used in the simulation is Wärtsilä 9L20C diesel engine. The exhaust pipe before SCR reactor is 2m long and 0.4m in diameter. A GK static mixer unit is equipped in the pipe and placed at various locations along the pipe. The length of GK static mixer unit is designed equal to the diameter of the pipe for the purpose of easy calculation. Under full load of the engine, the mass flow rate of the exhaust is 3.43kg/s with the exhaust temperature of 623K. Ammonia is introduced to the exhaust pipe from the centre of the inlet of the pipe. The boundary conditions for the inlet and outlet of the exhaust pipe are set for mass flow inlet and pressure outlet respectively. The turbulent flow is described by a *k-ε* model. A GK static mixer unit is placed at locations between 0.4m to 1.5m away from the ammonia injection point. The volume ratio of ammonia to exhaust varies at c=0.1, c=0.01 and c=0.001, respectively. Fig 1 is an illustration of the simulation model.

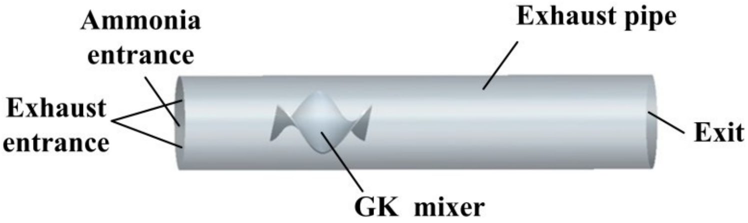

Fig 1: simulation model including exhaust pipe and a GK static mixer unit

EVALUATION OF MIXING QUALITY

A standard deviation is commonly used to evaluate the mixing degree of ammonia with exhaust gas at a section. Here, the standard deviation is called coefficient of variation (CoV) which is defined in equation (1). CoV also can be used to evaluate velocity and temperature distributions of a flow. A large value of CoV means an uneven distribution of ammonia.[3] The mixing process can be assumed to be homogenous when the value of CoV is less than 5%.[4]

$$CoV = \frac{1}{\bar{\omega}}\sqrt{\frac{\sum_{\mathrm{j}=1}^{\mathrm{n}}(\omega_{\mathrm{j}}-\bar{\omega})^2}{n}} \tag{1}$$

The sampling points for CoV calculation should be selected widely at a section of the exhaust pipe. The concentration of ammonia at each sampling points are recorded to calculate the sectional CoV. More accurate CoV can be obtained if more sampling points are collected. In this work, forty five sampling points are chosen which basically satisfy the requirement of accuracy of CoV calculation. It has been observed that there is no obvious advantage of CoV calculation in the simulation when increasing the number of sampling points beyond forty five. The distributions of ammonia concentration fraction and sampling points at a cross-section of the exhaust pipe are illustrated in Fig 2. The intersection points on the grids indicate the positions of sampling points.

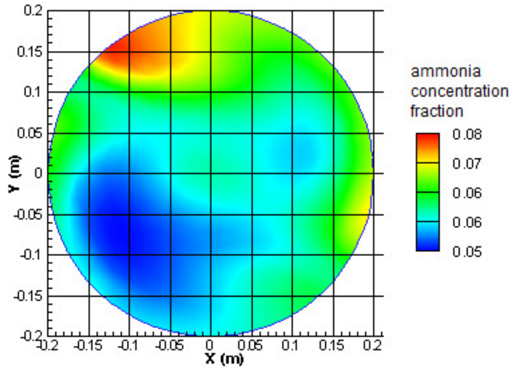

Fig 2: Distributions of ammonia concentration fraction and sampling points at a cross-section of the exhaust pipe

The CoV after static mixers is usually associated with that before static mixers, which is expressed in equation (2). [5]

$$CoV_{mixer\_out} = CoV_{mixer\_in}\square \qquad \frac{L_{mixer}}{D}) \tag{2}$$

Where, L_{mixer} is the length of static mixers and D is the diameter of exhaust pipe. B denotes the decreasing extent of CoV due to static mixers. In this case, $\frac{L_{mixer}}{D} = 1$, thus B is calculated as shown in equation (3):

$$B = \ln \frac{CoV_{mixer\_in}}{CoV_{mixer\_out}} \tag{3}$$

B is a coefficient which relates to the structure of static mixers and represents the mixing capacity of static mixers. It can be used as an index to evaluate the mixing capability of different static mixers.

Similarly, C also can be used as an index to evaluate the remaining mixing capability of the flow in the area after static mixers. This is because that mixing process may not only happen inside static mixers but also continue after static mixers. In that case, a length of one diameter of the pipe is used to calculate the remaining mixing capability of the flow after static mixers. C is calculated based on the following equation:

$$C = \ln \frac{CoV_{mixer\_out}}{CoV_{mixer\_out1D}} \tag{4}$$

Large values of B and C imply a good mixing performance of static mixers. Therefore, the mixing capacity of static mixers can be compared by contrasting the values of B and C. The positions used to calculate the sectional CoV of ammonia concentration are illustrated in Fig 3.

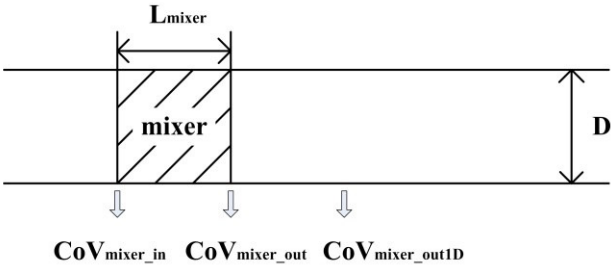

Fig 3: Illustration of CoV at each position

RESULTS AND DISCUSSION

Fig 4 and Fig 5 show the tendencies of the CoV of ammonia concentration at the exit of the pipe and at the entrance of the mixer changing with the location of GK mixer unit and the volume ratio of ammonia to exhaust respectively. The results suggest that both the values of the CoV of ammonia concentration at the exit of the pipe and at the entrance of the mixer change noticeably with the positions of GK mixer unit and the amount of ammonia injected. Fig 4 presents that small values of CoV are obtained at the exit of the pipe when GK mixer unit is placed close to the ammonia injection point. This suggests that static mixers placed upstream of an uneven flow can benefit the mixing since it can make full use of mixers. The value of the CoV at the entrance of the mixer indicates the mixing extent of ammonia and exhaust streams under a natural flow condition. It can be seen in Fig 5 that small values of CoV are obtained at the entrance of the mixer if there is a long distance for natural mixing. Both Fig 4 and Fig 5 show that the values of CoV decrease with the increase of volume ratio of ammonia to exhaust, implying that the mixing of ammonia and exhaust streams becomes easier if more ammonia is injected.

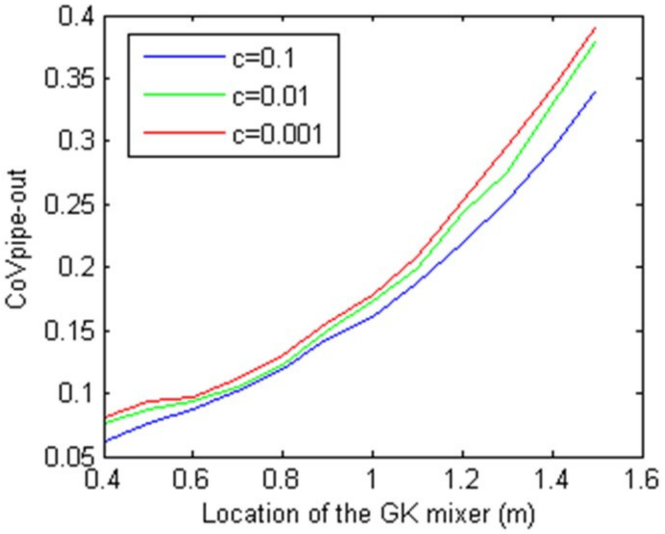

Fig 4: CoV of ammonia concentration at the exit of the pipe changing with the location of GK mixer unit and the volume ratio of ammonia to exhaust

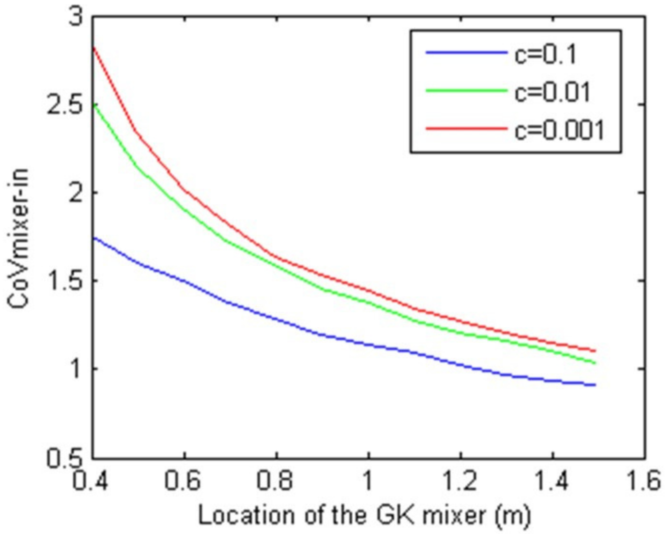

Fig 5: CoV of ammonia concentration at the entrance of the mixer changing with the location of GK mixer unit and the volume ratio of ammonia to exhaust

Accordingly, Fig 6 and Fig 7 suggest that the calculated B and C for an identical GK mixer unit also change with these two factors. Both B and C decrease with the increases of volume ratio of ammonia to exhaust and the distance between ammonia injection point and GK mixer unit. The explanation of the result may be that both B and C change with the value of CoV at the entrance of the mixer. In other words, the mixing performance of an identical static mixer may behave discrepantly under different flow conditions if using B and C as the evaluating indexes for mixing homogenisation.

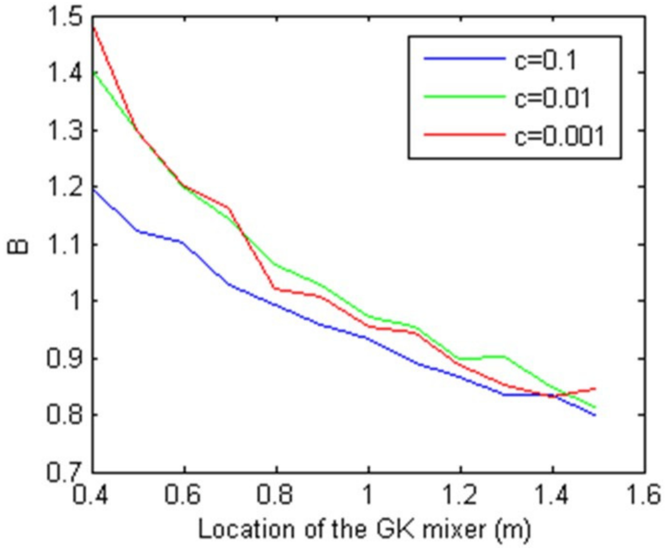

Fig 6: B changing with the location of GK mixer unit and the volume ratio of ammonia to exhaust

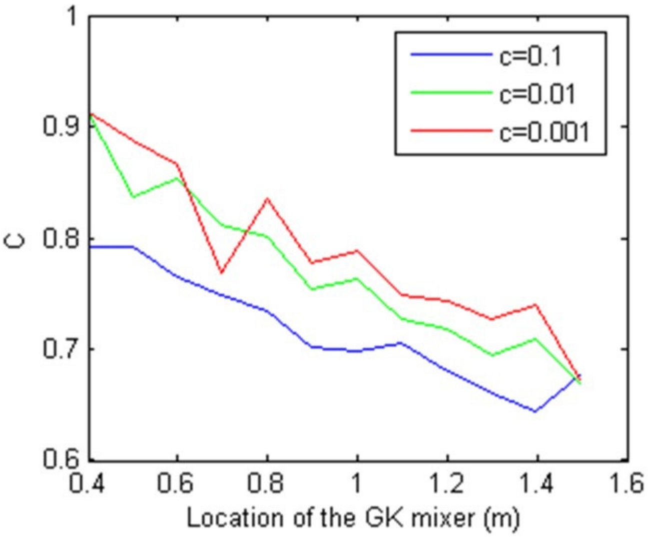

Fig 7: C changing with the location of GK mixer unit and the volume ratio of ammonia to exhaust

It can be inferred from Fig 5 to 7 that large values of B and C can be obtained if a large value of CoV exists at the entrance of static mixers. That is to say, static mixers may exhibit much better mixing performance under an extremely uneven flow if adopting B and C as the indexes to evaluate the mixing capacity of static mixers. This is reasonable that static mixers are useless if they are equipped under an extremely homogenous flow. The values of B and C calculated of static mixers thus equal zero since there is no advance of mixing homogenisation of the flow after static mixers.

CONCLUSIONS

This paper presents the indexes for evaluating the mixing capacity of static mixers. The effects of the location of static mixers and the volume ratio of two species on mixing quality have been investigated. The results show that more homogenisation of ammonia distribution can be achieved at the exit of the pipe if static mixers are placed close to the ammonia injection point or more ammonia is injected. Both B and C change with the value of the CoV of ammonia concentration at the entrance of static mixers. This implies that the mixing performance of an identical static mixer may behave discrepantly under different flow conditions if using B and C as the evaluating indexes for mixing homogenisation. Thus, it is necessary to consider all the factors which may affect the mixing quality of a flow when comparing the mixing performance of different static mixers.

ACKNOWLEDGEMENTS

This study was supported by Postdoctoral Scientific Research Developmental Fund of Heilongjiang Province (grant no. LBH-Q14038) and National Natural Science Foundation of China (grant no. 51109049)

NOMENCLATURE

c	volume concentration fraction of ammonia
ω_j	ammonia concentration at each sampling point
$\bar{\varpi}$	average value of ammonia concentration
n	number of sampling points
CoV	coefficient of variation
L_{mixer}	length of static mixers
D	diameter of exhaust pipe
B	index for evaluating the mixing capacity of static mixers
C	index for evaluating the mixing capacity of static mixers

REFERENCES

1. Koebel M, Elsener M, Kleemann M. 2000. *Urea-SCR: a promising technique to reduce NOx emissions from automotive diesel engines*. Catalysis Today. **59**(3-4):335-345

2. Björn T, Wouter O, Albert VDB. 2005. *Ammonia sensors and their applications—a review*. Sensors and Actuators B: Chemical. **107**(2): 666–677

3. Grosz-Röll F. 1980. *Assessing homogeneity in motionless mixers*. Int. Chem. Eng. **20**(4): 542-549

4. Kukukova A, Aubin, J, Kresta, SM, 2009. *A new definition of mixing and segregation: Three dimensions of a key process variable*. Chemical Engineering Research and Design. **87**(4): 633-647

5. Thakur RK, Vial Ch, Nigam KDP, Nauman EB, Djelveh G. 2003. *Static mixers in the process industries----a review.* Chemical Engineering Research and Design. **81**(7):787-826