A Design Optimization of Vortex Generator for Mixing Quality Improvement of a Gas Mixer for Syngas Engine Using Three-Dimensional CFD Modeling

Dominicus Danardono[1]*, Kim Ki-Seong[2] and Eko P. Budiana[1]

1. Department of Mechanical Engineering, Faculty of Engineering,
University of Sebelas Maret, Jl. Ir. Sutami 36A, Surakarta 57126
2. Department of Mechanical Design Engineering,
Chonnam National University, Jeonnam 550-749, Korea
*Corresponding author: danar1405@yahoo.com

Abstrak

A gas mixer is designed for mixing air and synthesis gas or “syngas” as fuel. Computational models are used to predict and analyze the influence of the vortex generator angle and aspect ratio on the mixing characteristics and performance of the gas mixer. Attention is focused on the vortex generator effect on the air-fuel ratio, pressure loss and mixing quality. Based on the numerical results, a vortex generator is designed. The gas mixer using the proposed vortex generators was realized with λ in the range of 1.7 to 1.1 corresponding to pressure loss in the range of 31.9 to 41.4 Pa at 100 m^3/h air-flow rates and coefficient of variation (CoV) of mixing in the range of 0.26 to 0.29.

Keywords: Air-fuel ratio, Pressure loss, Mixing quality, Vortex generator, Gas mixer, CFD

Introduction

A gas mixer is model (Fig. 1) is designed to mix synthesis gas (syngas) as a fuel and air for a stationary reciprocating engine. The gas mixer for the engine is designed to have air-fuel ratio in term of lambda (λ) in the range of 1.1 to 1.7. The gas mixer design model has simple construction and low air-fuel ratio with relatively small pressure loss, but, it does not produce good mixing quality. In this research, we focus on increasing the mixing quality of the gas mixer without significantly increasing pressure loss by using vortex genarators.

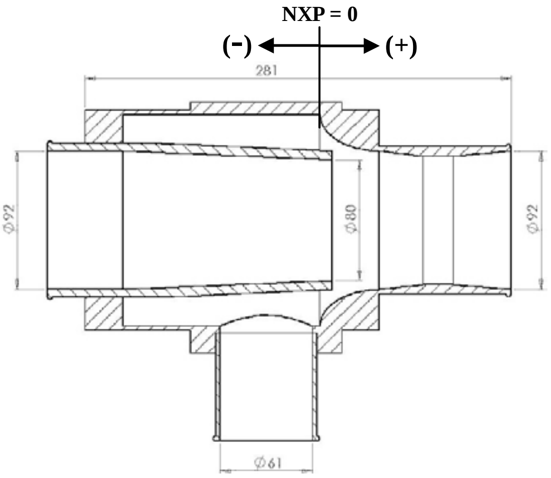


Figure 1. Schematic view of the gas mixer without mixing improvement device.

A passive control method using mechanical tabs at a nozzle exit as vortex generators has been known to be efficient. Most of the previous works proposed triangular shaped (delta) tabs with a 90^0 apex angle and orientation angle measured from upstream is 135^0 (Hu et al 2002, Zaman et al 1994). The mechanical tabs can increase the jet mixing performance in a low speed jet as well as in a high speed jet. The mechanical tabs can enhance jet mixing because each tab can generate large-scale streamwise vortices that responsible for flow distortion (Zaman et al 1994).

A type of static mixer is the high efficiency vortex (HEV) mixer. They can generate large-scale streamwise vortices, enhancing momentum-transfer phenomena and turbulent energy dissipation in the flow, much better than some static mixers known for high efficiency (Habchi et al 2010, Thakur et al 2003). However, better mixing performance is generally accompanied with an increase in the pressure drop.

The classical HEV mixer (Chemineer 1998) consists of rows of mixing tabs in a circular pipe. Each row is made up of four trapezoidal inclined tabs diametrically opposed in the tube cross section and fixed on the pipe wall and the tabs are aligned in the flow direction. Each tab of the HEV static mixer generates a pair of streamwise counter-rotating vortex pair (CVP) and hairpin vortices that produce vigorous cross-stream mixing and rapid uniformity (Bakker & Laroche 2000, Dong & Meng 2004, Habchi et al 2010, Mokrani et al 2009, Yang et al 2001). The tab inclination greatly affects the mixing. A larger tab inclination angle produces better mixing but at the expense of a larger pressure drop across the tab (Dong

& Meng 2004).

Experimental Methode & Facility

Mechanical tabs, following the design of the HEV static mixer, attached on the primary nozzle exit circumference to improve the mixing quality are modeled. The geometries and number of the mechanical tabs are modified and varied, and each modification is studied by using Computational fluid dynamics (CFD) package software to understand the influence of the mechanical tabs on the performance of the gas mixer.

The mixing quality of the gas mixer can be evaluated by determining the coefficient of variation (CoV) of mixing on the gas mixer outlet cross-section area (Etchells & Meyer 2004, Thakur et al 2003). The coefficient of variation can be evaluated as:

$$CoV = \frac{S}{\bar{c}} = \frac{\sqrt{\frac{1}{J-1}\sum_{j=1}^{J}(c_{1,j}-\bar{c})}}{\frac{1}{J}\sum_{j=1}^{J}c_{1,j}}$$

Based on the numerical results, an optimized design of the mechanical tabs is proposed. The optimized mechanical tabs should improve the gas mixer's mixing quality with low pressure loss.

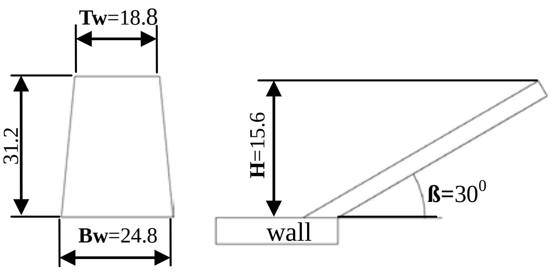


Figure 2. Mechanical tabs initial geometry and dimensions

The initial design of the mechanical tabs based on previous research of the HEV static mixer (Habchi et al 2010) is shown in Fig. 2. The variations and dimensions of the mechanical tabs are given in Table 1.

Table 1. Variations and dimensions of mechanical tabs

Tab angle variation ß (deg)	Tab aspect ratio variation H (mm)	Tw (mm)	AR	NXP Variation Mm
30	13.71	24.8	1.81	4
45	15.60	18.8	1.21	8
60	18.09	12.8	0.71	12
90	21.53	6.8	0.32	16
120	27.45	0.0	0.00	

Numerical Scheme

In this research, three-dimensional simulation models were made and analyzed by using the commercially available Star CD v3.26 code. The surface mesh of the mixers was generated using pro-STAR/surf, and hybrid meshes of the fluid volumes were constructed using pro-STAR/amm (Fig. 3). Hybrid meshes have a hexahedral core with pyramidal and tetrahedral cells that automatically produce a high quality versatile grid.

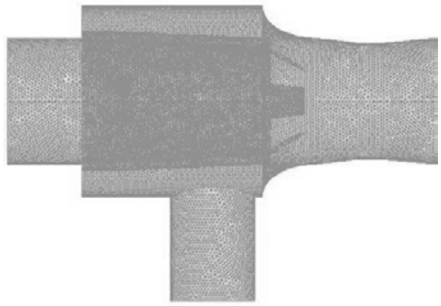


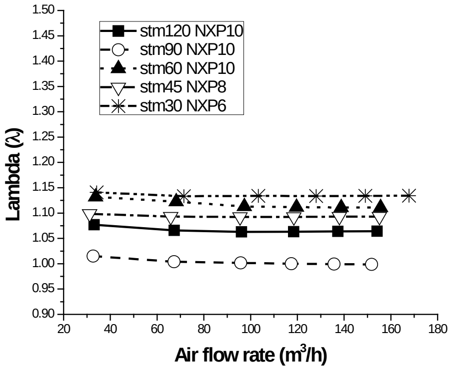
Figure 3. Gas mixer using mechanical tabs computational model with hybrid mesh generation.

Grid dependence test was performed on the model in order to obtain grid independent modeling result. Numbers of iteration were conducted by refining the mesh in every stage of simulation. After several simulations, it was found that the model would have consistency in result if the mesh consist grid cells more than about 480,000 cells. In this study, the grid cell volume used in the CFD simulation was set for about 500,000 cells.

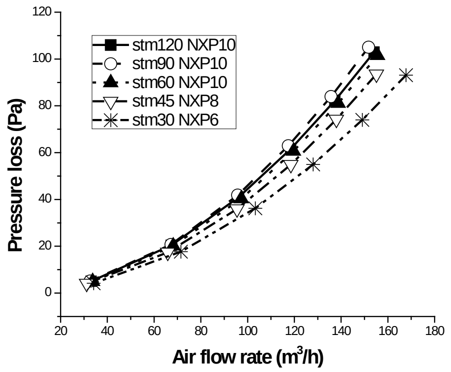
The computation models were run in the steady state condition. The turbulence model used in this calculation is the Standard k-ε model/ high Reynolds number, which was chosen because of its wide use, validated consistency and reliability, and less computer time (Habchi et al 2010, Sundararaj & Selladurai 2008, Utomo et al 2008). The near wall was defined by the standard wall function, which gives reasonably accurate results for a wall bounded with high Reynolds number flow. SIMPLE (Semi-Implicit Method for Pressure Link Equation) method was used as the solution algorithm because it can accommodate steady state calculations in the iterative mode.

Result and Discussion

To obtain nearly the same air fuel ratio for all of the tab angles, the primary nozzle exit position of the gas mixer with tab angle 30^0 was adjusted on NXP 6 mm, tab angle 45^0 on NXP 8 mm and the rest of the tab angles were set on NXP 10 mm. The calculation result is shown in Fig. 4.



(a). Air-fuel ratio



(b). Pressure loss

Figure 4. Mechanical tabs inclined angle variation calculation results with 1.01< λ <1.15.

The 30^0, 45^0 and 60^0 tab angle gas mixer at NXP 6 mm, 8 mm and 10 mm respectively, had similar air-fuel ratio, in the range of 1.1 to 1.15. The 30^0 tab angle gave the lowest pressure loss than the other tab angles, which was followed by 45^0 tab angle. The mixing quality of the gas mixer using mechanical tabs can be seen in Fig. 5.

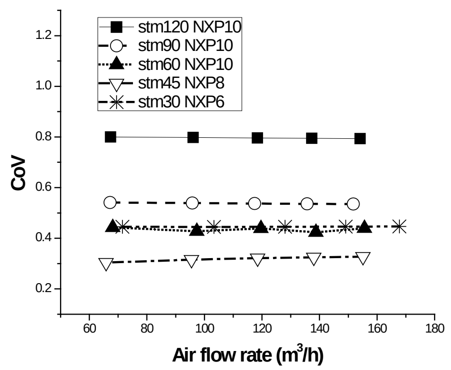
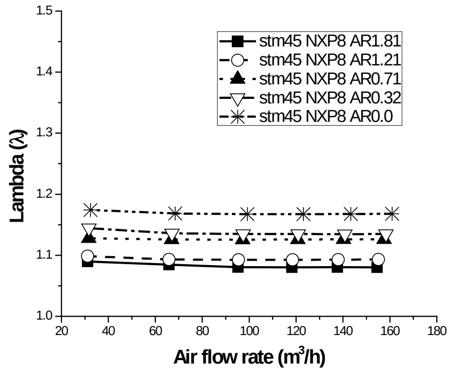


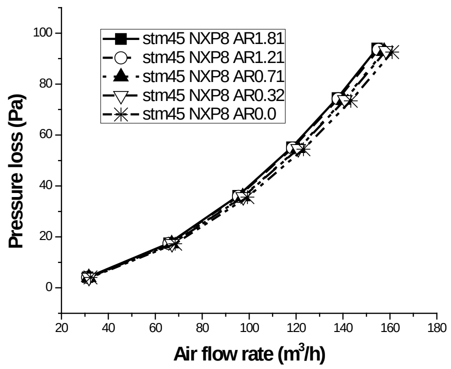
Figure 5. Mixing quality of the gas mixer using mechanical tabs according to inclined angle

The 60^0 and 30^0 tab angles gave similar CoV values and better mixing quality than the 90^0 and 120^0 tab angles. However, the 45^0 tab angle showed the best mixing quality.

The mechanical tabs AR is varied for tab inclined angle of 45^0. The projected area to the vertical plane of the all tabs is the same. The calculation results are shown in the Fig. 5. The results show that reduces the AR will increase the air-fuel ratio with a slight decrease on the pressure loss. Decreasing the tab aspect ratio can improve the mixing quality (Fig. 6). However, when the AR equals 0.32, the mixing quality achieves the maximum value (lowest CoV). Further decrease in AR will reduce the mixing quality.



(a). Air-fuel ratio



(b). Pressure loss

Figure 5. Results according to tab aspect ratio

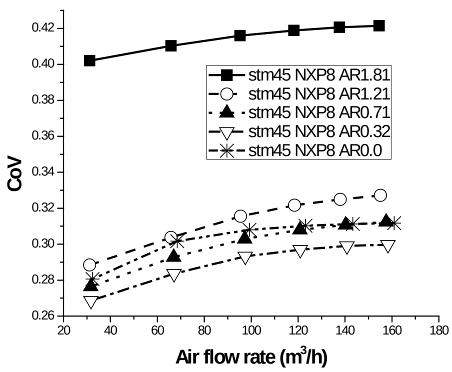
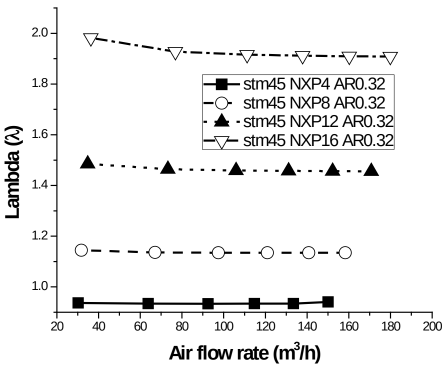


Figure 6. Mixing quality of the gas mixer using mechanical tabs according to tab aspect ratio

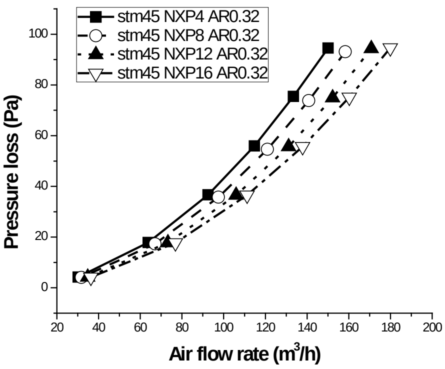
It is found out that the optimum tab angle is 45^0.

This tab angle can produce much better mixing quality than the other tab angles. The best mixing performance is obtained with AR of 0.32. Therefore, a vortex generator with 45^0 tab angle and AR 0.32 is selected as the optimized design.

Fig. 7 shows the calculation results of the optimized gas mixer with mechanical tabs at different NXP. The NXP are 4, 8, 12 and 16 mm from the entrance of the gas mixer mixing chamber. It is shown that retracting the primary nozzle away from the gas mixer mixing chamber increases the secondary flow (fuel) rate into the mixing chamber, thus lowering the air-fuel ratio. Consequently, the pressure loss is also increased. The influence of the NXP on the air-fuel ratio and pressure loss at 100 m^3/h air-flow rate is depicted on Fig. 16. It can be seen that gas mixer at 5.3 < NXP < 14.1 mm gives the required air-fuel ratio, λ from 1.1 to 1.7, and pressure loss in the range of 31.9 to 41.4 Pa.



(a). Air-fuel ratio



(b). Pressure loss

Figure 7. Optimized model of gas mixer according to NXP.

Fig. 8 shows that the mixing quality at the outlet of the optimized gas mixer decreases as the primary nozzle retracts away from the mixing chamber.

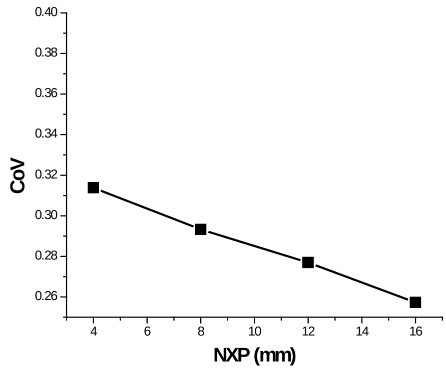
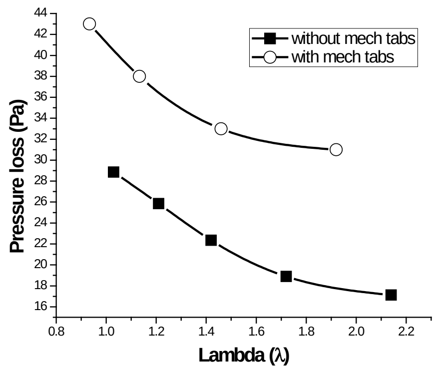
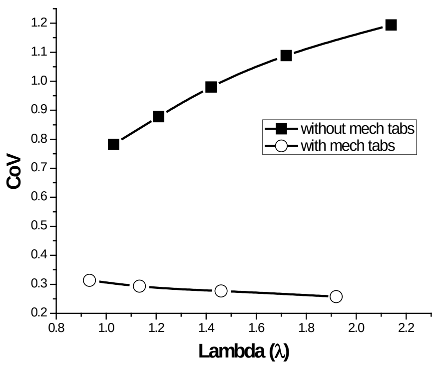


Figure 8. Influence of NXP on the mixing quality at air-flow rate 100 m^3/h.



(a) Pressure loss on various λ



(b) CoV on various λ

Figure 9. Comparison of the gas mixer without mechanical tabs and with mechanical tabs at various NXP (air-fuel ratio) at air-flow rate of 100 m^3/h.

Comparison between the gas mixer with and without mechanical tabs vortex generator at 100 m^3/h air flow rates, as depicted in Fig. 9, shows that better mixing performance is accompanied by increased pressure loss. However, the increased pressure loss by the mechanical tabs is relatively small in the range of about 11.5 to 12.8 Pa. The mixing performance of both gas mixers shows different characteristics. In case of the gas mixer without mechanical tabs, as the air-fuel ratio increases, the mixing quality is decreased. On the other hand, the mixing quality of the gas mixer with mechanical tabs increases with the air-fuel ratio. The CoV of mixing of the gas mixer with mechanical tabs vortex generator is in the range of 0.26 to 0.29, while the gas mixer without mechanical tabs vortex generator is in the range of 0.82 to 1.08.

Conclusion

In this research, a computational study was performed to investigate the performance of the gas mixer using mechanical tabs as a vortex generator and to develop an optimized design of the mechanical tabs. A trapezoidal vortex generator configuration was found to be effective in improving the gas mixer's mixing quality. The tab angle had stronger effect on the mixing performance than the tab aspect ratio. The optimum design of the mechanical tab was realized with 45^0 tab angles and aspect ratio of 0.32.

The gas mixer with the mechanical tabs had much better mixing performance than the gas mixer without mechanical tabs with only relatively small increase in pressure loss. The design range of the gas mixer's air-fuel ratio can be fulfilled by setting the primary nozzle exit position in range of 5.3 < NXP < 14.1 mm, which would yield a pressure loss in the range of 31.9 to 41.4 Pa and CoV of mixing in the range of 0.26 to 0.29.

Nomenklatur

H	Height of tab projected to the plane perpendicular to the flow direction (mm)
S	Standard deviation of concentration measurements
J	Number of sample
c	Measurement sample concentration
$\bar{c}$	Mean concentration
T_W	Top width of the tab (mm)
B_w	Bottom width of the tab (mm)
AR	Tab aspect ratio (T_w : H)
NXP	Primary nozzle exit position (mm)
CoV	Coefficient of Variation
ß	Tab inclined angle
λ	Air-fuel ratio gravitational constant (ms^{-2})

Greek letters

ß	Tab inclined angle
λ	Air-fuel ratio

Referensi

Bakker A, Laroche R D. Modeling of the turbulent flow in HEV static mixers [EB]. *The Online CFM Book* (2000).

Chemineer, Kenics, Static Mixing Technology [EB]. *Chemineer Inc.*, Bulletin 800 (commercial documentation) (1998).

Dong S, Meng H. Flow past a trapezoidal tab [J]. *Fluid Mech*, (2004) vol. 510, pp. 219-2472 (2004).

Etchells III A W, Meyer C F. *Mixing in pipelines, Handbook of Industrial Mixing: Science and Practice* [M]. John Wiley & Sons, Inc, New Jersey (2004).

Habchi C, Lemenand T, Valle DD, Peerhossaini H. Turbulent mixing and residence time distribution in novel multifunctional heat echangers-reactors [J]. *Chemical engineering and processing: process intensification* (2010).

Hu H, Kobayashi T, Saga T, Taniguchi N. Stereoscopic PIV Measurement of a jet flow with vortex generating tabs [J]. *The 10th International Symposium on Flow Visualization*, August 26-29, Kyoto, Japan (2002).

Mokrani A, Castelain C, Peerhossaini H. Experimental study of the influence of the rows of vortex generators on turbulence structure in a tube [J]. *Chemical Engineering and Processing*, 48 (2009) 659-671 (2009).

Sundararaj S, Selladurai V. An analysis on proportional mixing of liquids using venturi jet mixer [J]. *International Journal of Applied Engineering Research*, 7 (2008) 891-902 (2008).

Thakir RK, Vial Ch, Nigam KDP, Nauman EB, Djelveh G. Static mixer in the process industries – A review [J]. *Trans IChemE*, Vol. 81, Part A (2003).

Utomo T, Jin Z, Rahman M Sq, Jeong H, Chung H. Investigation on hydrodynamics and mass transfer characteristics of a gas-liquid ejector using three-dimensional CFD modeling [J]. *Journal of Mechanical Science and Technology*, 22 (2008) 1821-1829 (2008).

Yang W, Meng H, Sheng J. Dynamics of hairpin vortices generated by a mixing tab in a channel flow [J], *Experiments in Fluids*, 30 (2001) 705-722 (2001).

Zaman KBMQ, Reeder MF, Samimy M. Control of an axisymmetric jet using vortex generators [J]. *Physics Fluids*, 6 (2) (1994).