Numerical study on dissimilar guide vane design with SCC piston for air and emulsified biofuel mixing improvement

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Abstract. Crude palm oil (CPO) is one of the most potential biofuels that can be applied in the conventional diesel engines, where the chemical properties of CPO are comparable to diesel fuel. However, its higher viscosity and heavier molecules can contributes to several engine problems such as low atomization during injection, carbon deposit formation, injector clogging, low mixing with air and lower combustion efficiency. An emulsification of biofuel and modifications of few engine critical components have been identified to mitigate the issues. This paper presents the effects of dissimilar guide vane design (GVD) in terms of height variation of 0.25*R*, 0.3*R* and 0.35*R* at the intake manifold with shallow depth re-entrance combustion chamber (SCC) piston application to the in-cylinder air flow characteristics improvement. The simulation results show that the intake manifold with GVD improved the performance of the air flow characteristic particularly swirl, tumble and cross tumble ratios from the intake manifold to the engine. The GVD with the height of 0.3*R* was found to be the optimum design with respect to the overall improvement of the air flow characteristic. The improvement of the air flow characteristic with the application of GVD and SCC piston in the engine was expected to contribute to a better air fuel mixing, fuel atomization and combustion efficiency of the engine using emulsified biofuel as a source of fuel.

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1 Introduction

Diesel engine becomes most important and reliable power source generation nowadays for its high thermal efficiency, high compression ratio and inherent lean burn which enable heat dissipation via excessive air. The diesel engine application is widely used in the industrial, transportation and agriculture application [1]. However, diesel engines have drawbacks of an enormous poison emission particularly soot, hydrocarbons (HC), nitrogen oxides (NO_x), sulfur dioxide (SO_x), carbon monoxide (CO) and particulate matter (PM). This emission contributes to a detrimental human health and risk to the ecological system. The stringent policies in many European countries have alerted both heavy and light engine manufacturers to introduce the engines that can fulfil clean and green technology. In order to pursue this matter particularly in combustion efficiency, several strategies and methodologies have been made such as the development of internal combustion engine designs; combustion chamber and intake manifold, injection strategies and elevated injection pressure pump and dual strategy [2]. Numerous researchers reported that the global energy demand will increase progressively, e.g. in 1980, the fuel demand was 6630 million tons of oil in equivalent (Mt), and by 2030, the fuel consumption demand will expected to increase to 53% [3-5]. For this reason, the searching for alternative fuels to offset the global demand of fuel consumption becomes more challenging in order to minimize the fossil fuel dependence and subsequently improve the quality of the ecological system.

It attracts many researchers to explore the potential application of crude palm oil (CPO) as an alternative fuel since it is widely available and can be mass produced. CPO uses less land energy to fertilizer than other resources and it is capable to produce ten times energy of it consumes [6]. However, a direct application of CPO in the conventional diesel engines will leads to several issues such as less efficient combustion process due to retardation of the atomization process and change of timing in ignition delay [7-8]. According to Maher et al [9], high viscosity and low volatility of CPO, the engine will confront problem i.e. carbon deposited formation. This is because of poor atomization and incomplete combustion due to large triglyceride molecule and their high molecule mass. To tackle this issue, the combustion efficiency has been highlighted by increasing the rate of evaporation and mixing biofuel into the air. One of the feasible methods is assisting the air flow such as swirl and tumble in the in-cylinder. Swirl is defined as a rotational flow about the vertical axis [10-11]. Tumble is defined as the rotational flow about an axis perpendicular to the vertical axis of the cylinder [12]. Cross tumble is defined as a rotational flow about an axis perpendicular to both swirl and tumble axes [13].

Hence, this paper proposed the dissimilar guide vane design (GVD) for enhancing the swirl and tumble air flow in the fuel injection region area (piston-bowl) and expected to aid the mixing homogeneously between emulsified biofuel and air. A computational fluid dynamic (CFD) solver is utilized to predict the best design of GVD that will improved the air flow characteristics in term of air fuel mixing, fuel atomization and combustion efficiency.

2 Methodology

In general, the curve vane assisted the air into combustion chamber by either swirl or tumble and their turbulence kinetic energy (TKE) inside it's really important. Saad et al. [13] demonstrated that the effect of various design of their devise namely guide vane swirl and tumble device (GVSTD). Their investigation shows that the GVSTD has been proven to improve air flow and eventually improve the combustion efficiency. To enhance the swirl flow, the large vane surface is required [14]. However, the large vane surface will obstacle the air flow and create a high resistance of flow [15]. Enlarge the vane size will benefit to the momentum of air flow but a loss in volumetric efficiency.

2.1 Design of GVD

The effectiveness of height vane configuration via air flow arrangement for suitability emulsified biofuel application is utterly focused in this research. Four vanes which equally space are equipped in the diameter of inlet manifold air inlet runner. The GVD specification is listed in Table 1 and their schematic diagram is shown in Fig. 1.

Table 1. Specification of the guide vane design (GVD).

No.	Parameter	Value
1	Number of Vane	4
2	Length of vane (*l*)	30mm
3	Width of vane	0.5mm
4	Height of vane (*Hv*)	0.25R 0.30R 0.35R
5	Vane twist angle (θ)	35°
6	Angle of incident	90°

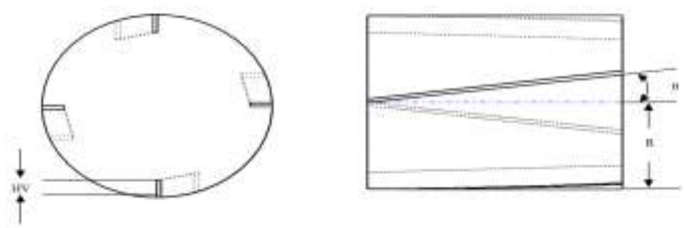

Fig. 1. Schematic diagram of GVD.

2.2 Governing equation

There are three fundamental physic principle involved, namely conservation of mass, conservation of momentum (Newton's second law) and energy.The equation for vector notation is express as below:

$$\frac{\partial \rho}{\partial t} + \nabla . [\rho \vec{u}] = 0 \quad (1)$$

where ρ is the fluid density and $\vec{u}$ is the three dimensional flow velocities in the *x, y, z* directions.
The equation for forces and surface force on the control volume:

$$\frac{\partial (\rho U)}{\partial t} + \nabla . (\rho U \times U) = -\nabla p + \nabla . \tau + S_M \quad (2)$$

where P, τ and S_M are the fluid pressure, strain rate and momentum source, respectively.
The energy equation is express as below:

$$\frac{\partial(\rho h_{tot})}{\partial t} - \frac{\partial p}{\partial t} + \nabla.(\lambda\nabla T) + \nabla.(U.\tau) + U.S_M \quad (3)$$

where h_{tot} and λ represent the total enthalpy and thermal conductivity of the fluid, respectively.

2.3 Grid independency test

The grid independent test (GIT) is a term usually used to describe the improvement via successively optimum cell sizes for analysis. Table 2 shows the case 3 was an appropriate meshing grid due to less nominal deviation.

Table 2. Summary of Grid Independency Test (GIT)

Case	1	2	3	4	5
Elements	103242	256242	302309	370061	447626
Average Cylinder Pressure	2.594×10^6	2.599×10^6	2.661×10^6	2.661×10^6	2.661×10^6

2.4 Numerical validation

Fig. 2. shows the in-cylinder pressure against crank angle (θ) diagram for a 3D in-cylinder air flow simulation at speed 2000 rpm. It was shows the good in agreement between experimental and numerical result and slightly 7% difference at peak pressure.

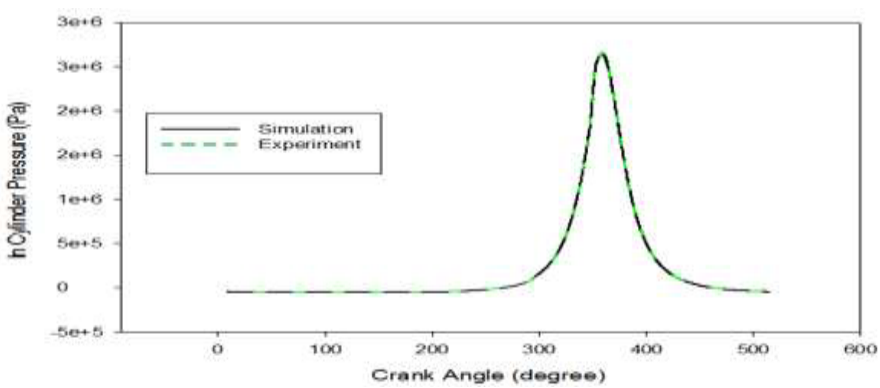

Fig. 2. In-cylinder pressure against crank angle (θ).

2.4 YANMAR L70AE diesel engine

The geometry of diesel engine was designed based on the Yanmar L70AE-D, engine speed in 2000 revolution per minutes (rpm) and their specification can be referred in Table 3. The diesel engine has been modelled using SOLIDWORK 2014, which considers the main six components of the model; intake runner, intake port, intake valve, cylinder, exhaust valve and exhaust port as can be seen in Figure 3. The components were assembled together to become one solid part before exporting to ANSYS- Design Modeller 15. The both valves; exhaust valve and intake valve were assigned as solid parts and the remaining were assigned as a fluid domain. Meanwhile, Figure 4 shows the GVD installed at the intake manifold.

Table 3. Specification of the engine

No.	Parameter	Value
1	Type	YANMAR L70AE-D
2	Bore	78mm
3	Stroke	62mm
4	Compression ratio	19.1
5	Intake Air	Natural Aspirated
6	Type of piston head	Bowl in-cylinder
7	Engine Speed	2000 rpm

No	Name
1	Intake Port
2	Intake Valve
3	Exhaust Port
4	Exhaust Valve
5	Bowl in SCC Piston
6	Clearance Volume

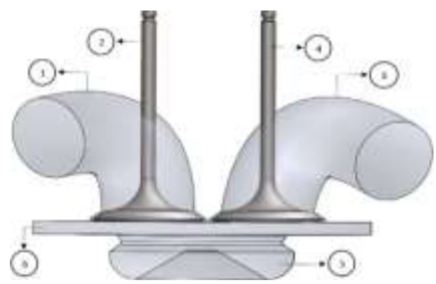

Fig. 3. Engine components.

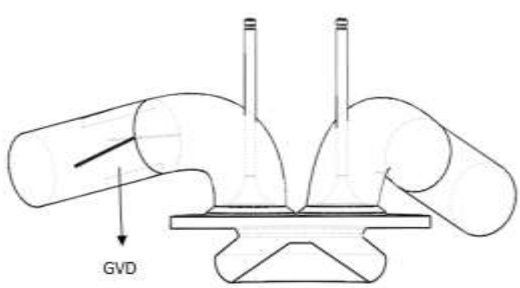

Fig. 4. GVD installation at the intake manifold.

The engine simulation was operated with a utilization of moving mesh to represent the motion of piston. The course mesh until the ultra-fine mesh sizes were verified and accomplished for better accuracy result and the optimization of meshing will save computational cost and time. The continuity, momentum and energy equations were used to compute this analysis and can be found at ANSYS FLUENT 15 solver theory guide. The initial pressure and temperature were set at 1atm and 300K respectively.

3 Results and discussion

3.1 Swirl Ratio, Tumble and Cross Tumble Ratio

Fig. 5 shows the swirl ratio against crank angle (θ) for three dissimilar models with GVD and no GVD installing at the air intake manifold. Swirl ratio with higher value promotes a better mixing of fuel and air homogeneously and aids the combustion efficiency. It is because of the swirl ratio is determined by their air flow pattern and their strength characteristics. The highest ratio of swirl will stimulate the better air mixing with low-grade and low volatility fuel. The ratio value either positive or negative value ratio is arbitrary. Thus, the important value to concern is a magnitude of the ratio. Based on Fig. 5. It shows that the air swirl ratio is produced higher once considering the GVD installation and consequently improves the air swirl ratio. The *0.3R* type of GVD produced higher of swirl ratio on the position start of injection (SOI) at 346° approximately 70% significant different compared to no GVD. The *0.25R* and *0.35R* also improved the swirl ratio approximately 14% and 22% respectively compared to no GVD. It clearly indicates that the result after considering GVD is a good agreement with Bari et al [17] whereby after consider the guide vane swirl tumble device (GVSTD), the air swirl flow characteristic is elevated instead of uninstalled GVSTD.

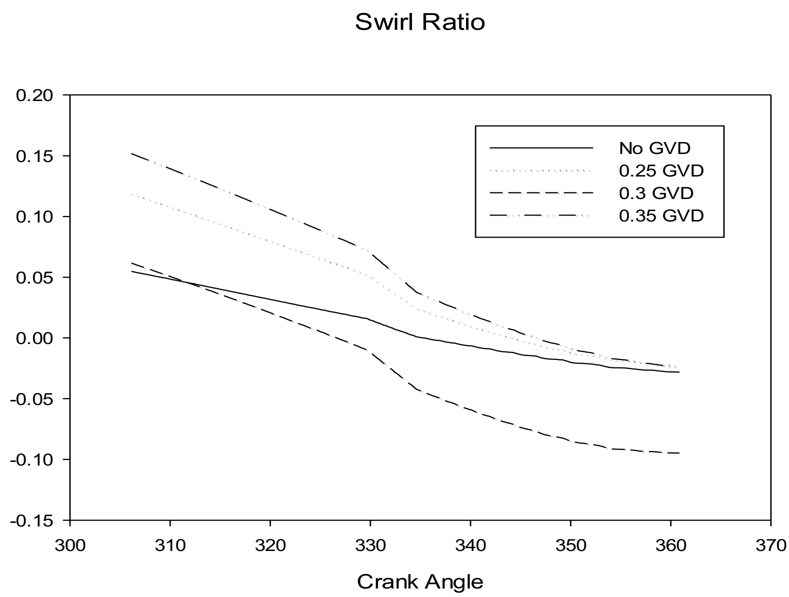

Fig. 5. Swirl ratio against crank angle (θ) with and without GVD.

Fig. 6. Shows the tumble and cross tumble ratio against crank angle (θ). In combustion theory, the effect of tumble and cross tumble are similar to swirl ratio which derive to the enhancement of turbulence flow and assist mixing fuel and air along the piston-bowl in a homogenous mixture. Fig. 6. (a) and (b) present the tumble and cross tumble ratio with installed GVD has significantly higher and strong magnitude ratio rather than the engine without GVD. Fig. 6. (a) Shows the tumble ratio which present the *0.3R* and *0.35R* type of GVD has higher tumble ratio and parallel both of them in term of magnitude ratio during SOI. Both of them has significantly difference approximately 75% compared to no GVD. Nevertheless, Fig. 6. (b) Shows the *0.35R* type of GVD has higher cross tumble ratio and approximately 60% significant difference with no GVD. This result implies that, once

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installing the GVD in the intake manifold substantially will give a stronger lateral flow of air within the cylinder. The lateral flow will assist the injected fuel spreading via consistent flow along the piston bowl.

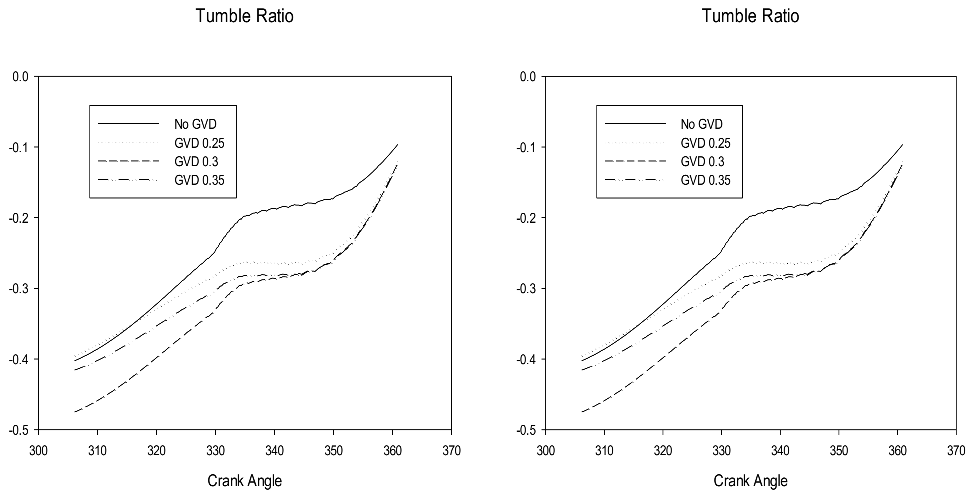

Fig. 6. (a) Tumble ratio against crank angle (θ) and (b) Cross tumble ratio against crank angle (θ).

3.2 Turbulence Kinetic Energy (TKE)

TKE is the mean kinetic energy per unit mass that is associated with eddies in turbulence flow [18]. TKE is mainly concern due to the capability of the energetic turbulence to assist the atomization molecule along the piston-bowl of the fuel flow. For the conventional diesel fuel, the atomization spraying profile injection is wide cone angle and short penetration during injection while the atomization profile for the emulsified biofuel is vice versa. The higher value of TKE implies that smoother and more efficient combustion, promotes the flame propagation, reduce carbon deposited and aid in break-up length penetration to mix with wide area inside the combustion chamber. From Fig. 7. It shows that the GVD has significant value of TKE at the start of combustion (SOC) at 352° compared to without GVD. The *0.3R* type of GVD has been overtake the no GVD TKE during SOC and leads higher until to top dead centre (TDC). However, during SOI at the crank angle 346°, the no GVD shows the good TKE rather than installing GVD and approximately 10% significant different compared to the *0.3R* type of GVD. Despite of installing GVD will detrimental TKE at SOI, nevertheless installing GVD will improve SOC and contribute in combustion efficiency, the detrimental of SOI is considering fewer. The GVD with 0.3*R* is the excellent design among the others of GVDs. This result indicates that, installing the GVD has been proven in the improvement of the TKE and consequently aids in the flame propagation along the piston bowl.

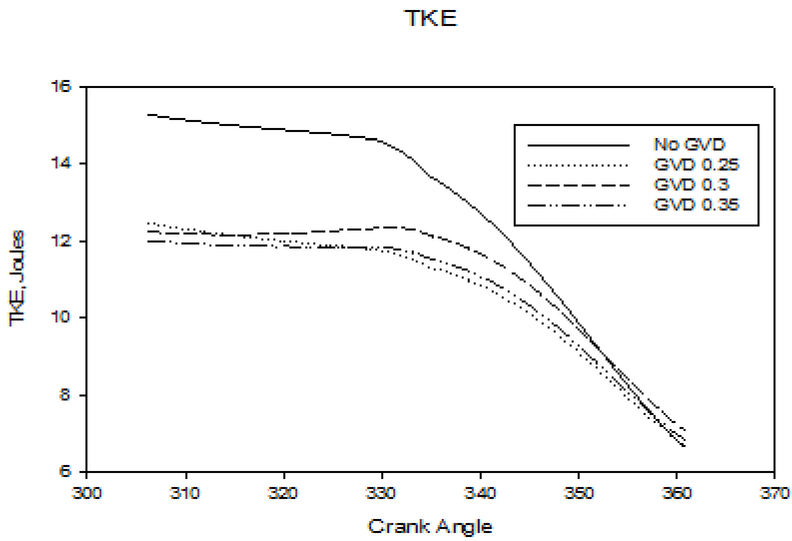

Fig. 7. In-cylinder TKE.

4 Conclusions

The effects of dissimilar GVD design in terms of height with SCC piston to the in-cylinder air flow characteristics have been studied. The in-cylinder air flow characteristics were measured and the profiles were developed via simulation in terms of swirl, tumble ratio, cross tumble ratio and turbulence kinetic energy. There was a significant improvement observed on the swirl, tumble and cross tumble ratios as a result of GVD installation in the intake manifold. The TKE result showed a higher turbulence producer which is essential in spreading atomization molecule along the piston bowl. The GVD with the height of $0.3R$ was found to be the optimum design that has contributed to the improvement of swirl, tumble and cross tumble ratios by 70%, 60% and 60%, respectively.

The GVD design was capable to increase the fuel dispersion in the cylinder and to break up the length penetration of the emulsified biofuel injection. The improved air flow characteristics can possibly mitigate the problems of carbon deposit formation on the piston bowl due to insufficient period of time to combust. Further investigation of GVD design parameters will be performed in order to determine the effects of vane length, vane angle, number of vane, thickness and diameter of the intake manifold to the overall improvement of the air flow characteristics.

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