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Optimize Vane Length to Improve In-Cylinder Air Characteristic of CI Engine Using Higher Viscous Fuel

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Abstract. Environmental issues and the depletion of worldwide crude oil sources have developed the requirement for an alternative fuel to power internal combustion engines. Vegetable oil, waste cooking oil and biodiesel are all renewable, environmentally sustainable and compatible with current Compression Ignition (CI) engines with little to no engine modification necessary. These fuels however have a higher viscosity than conventional petro-diesel and may be referred to as Higher Viscous Fuels (HVF). HVF have reduced in-cylinder combustion efficiency when compared with petro-diesel which reduces the engine performance in terms of output power, torque and fuel efficiency. A possible solution to the reduced efficiency is through the use of a Guide Vane Swirl and Tumble Device (GVSTD). This device when installed in front of the air intake manifold may produce improved air flow characteristics. This improves the efficiency of the evaporation processes and air-fuel mixing and therefore improves overall combustion efficiency. The effect of GVSTDs on in-cylinder air flow was studied using 3D Internal Combustion (IC) engine simulation under motored engine conditions. This was done using ANSYS-CFX. The base model engine was adapted from the Hino W04D model CI engine. The model throughout all simulations was run at a constant speed of 1500 rpm. There are four parameters to consider for GVSTD models; vane length, vane height, vane angle and the number of vanes. For the purpose of this study, the vane height, vane angle and the number of vanes were maintained as constants leaving the vane length as the variable parameter. 11 GVSTD models were simulated each varying from 1.5 to 4.5 times the radius of the intake runner (R) in 0.3R increments. To analyze the air-flow characteristics, the maximum in-cylinder pressure, Turbulence Kinetic Energy (TKE) and velocity were measured. It was found that for the constant values for vane height, vane angle and the number of vanes of 0.2R, 35° twist angle and 4 perpendicularly-arranged respectively, the in-cylinder pressure, TKE and velocity were optimum for the vane lengths of 3.6 to 3.9 times R.

Introduction

Today the Internal Combustion (IC) engine is necessary for modern transportation needs. However, currently the continued use of IC engines presents two major problems; the depletion of crude oil worldwide and environmental issues [1]. The use of an alternative fuel may be the solution to both these problems. It is universally agreed that an alternative fuel should be both renewable and environmentally friendly [1]. Additionally, the fuel must be compatible with standard or minimally modified current IC engines and not require the production of entirely new IC engines. The alternative fuel will also need to have a high energy content to maintain output power, output torque and reduced fuel consumption.

Vegetable oil, waste cooking oil and biodiesel are widely considered to be the main potential alternative fuels. Vegetable oil, waste cooking oil and biodiesel are all renewable sources and are known as oxygen generated fuels which result in cleaner combustion than petro-diesel [2]. As these fuels are sourced from agricultural plantations, they produce a zero overall carbon footprint [3]. Additionally, these fuels can be used in compression ignition (CI) engines (otherwise known as diesel engines), with minimal engine modification or with no modification at all [4]. This can be done with the added advantage of a higher thermal efficiency than a petrol engine [5].

In some cases, the alternative fuel may have a flash point more than twice that of petro-diesel, be 5-12% denser than petro-diesel and the viscosity may be 5 to 15 times higher [6, 7]. For the reasons above, the alternative fuels may be referred to as Higher Viscous Fuel (HVF). The disadvantage of these fuel alternatives is that their high flash points, high viscosities and high densities reduce the combustion efficiency of CI engines and hence reduce overall performance in terms of output power, output torque and fuel efficiency [7, 8] and also filter clogging, higher carbon build up inside the chamber and higher emissions (in particular NOx gases at high engine load) [1, 4].

This combustion efficiency may be improved by preheating the HVF to 70°C-135°C prior to combustion and by blending 2.6% to 50% HVF with regular petro-diesel to reduce overall viscosity [7, 9]. However these techniques are not completely effective and the overall performance of alternative fuel powered engines is generally still lower than petro-diesel engines. Referring to the CI combustion theory [5], the fuel will be injected during compression stroke a few degree Crank Angle (CA) before Top Dead Center (TDC). The fuel then needs to evaporate and mix with air, then ignite quickly and effectively to produce the maximum energy. Improving the evaporation and mixing processes will result in an improved power output [5]. With HVF, the auto ignition will take longer time [6] because high viscosity and volatility will cause slow vaporization and air fuel mixing. One way to accelerate the evaporation and mixing process is to improve the in-cylinder air characteristic. The mixing process can be improved by increasing the air pressure, the Turbulence Kinetic Energy (TKE) and air velocity of in cylinder air. These improved air characteristics help break up the HVF and allow it to mix with air faster. The use of a Guide Vane Swirl and Tumble Device (GVSTD) is suggested for this reason. The GVSTD is to be installed in front of the air intake to produce a manageable and improved air flow in terms of air pressure, TKE and velocity. The GVSTD is designed with four main parameters: vane height, vane angle, vane length and the number of vanes. Due to the number of parameters, optimization becomes increasingly difficult.

Studies [2, 3] have found through simulation results of ANSYS-CFX 14.0 that the use of a GVSTD improves in-cylinder air pressure, TKE and velocity significantly. However, these studies optimized the GVSTD designs by changing the vane height variable only. For the purpose of this study, the vane length was the optimization variable. Similar to these previous studies, the CFD (Computational Fluid Dynamics) tool used was the ANSYS-CFX 14.0 program. ANSYS-CFX was used to produce cold flow IC engine simulations in transient mode.

For the purpose of this study, the vane length was taken as the variable, the constants for the remaining 3 parameters i.e. vane height, vane angle and the number of vanes were 0.2R, 35° twist angle and 4 respectively (0.2R is used to mean 0.2 times the radius (R) of the intake runner).

Computer Modeling

Computer modeling requires the development of simulation models, meshing and setting up boundary conditions before a simulation can be run. The naturally aspirated Hino W04D CI engine was used for the engine model. The Hino W04D was run at a constant speed of 1500 rpm for all simulations; see Table 1(a) for main engine data. The GVSTD models were developed and installed appropriately to the Hino W04D engine. The GVSTD models were developed with vane lengths ranging from 1.5R to 4.5R, in 0.3R increments see Table 1(b). Therefore 11 GVSTD models were designed in total (1.5R, 1.8R, 2.1R, 2.4R, 2.7R, 3.0R, 3.3R, 3.6R, 3.9R, 4.2R, 4.5R). The label 0.0R indicates the base model data, i.e. the engine model with no GVSTD installed.

The base engine and GVSTD models were developed using Solidworks 2010 as shown in Fig. 1(a) and Fig. 1(b) respectively. The in-cylinder flow of the motored engine was studied using the commercial CFD package ANSYS; ANSYS-DesignModeller, ANSYS-Mesh and ANSYS-CFX [10]. The models were developed using the Solidworks program. The files from Solidworks were then imported into ANSYS-DesignModeller and the materials for the models were assigned. From Fig. 1 both valves were set as solid domain while other components were set as fluid domain to produce realistic air flow conditions. ANSYS-Mesh was set to generate tetrahedral cells to allow moving mesh for the simulation to run. Settings for piston and valve timing were set in ANSYS-CFX for the engine running at constant 1500 rpm in accordance with Heywood [5] to allow the simulation to run effectively and accurately.

The equations for continuity, energy, momentum and Shear Stress Transport (SST) were used to run the simulation in accordance with the CFX-Solver Theory Guide [10]. The simulation was set to run from 0-1440°CA (2 cycles) and the initial conditions for pressure, temperature and velocity were set to 1 atm, 300 K and 0 m/s respectively. Running 2 cycles allowed the second cycle to use the data from the previous cycle as initial conditions. This is because of the difficulty of measuring initial conditions at 0°CA, the second cycle is intended to use the data from the first cycle as initial conditions, this produces an accurate and realistic result.

Table 1: (a) Technical specification of engine model – HINO W04D; (b) Specification of GVSTD models.

(a)

Engine Parameters	Value
Bore × Stroke	104 × 108 mm
Compression Ratio	17.9
Intake System	Naturally Aspirated
Piston Head	Concave convect piston bowl
Start of Injection	14°bTDC

(b)

GVSTD Parameters	Value
Number of Vanes (N)	4 vanes 90° to each other
Vane Twist Angle (θ)	35° Clockwise
Intake Runner Radius (R)	10 mm
Height of Vane (H)	0.2R
Lengtht of Vanes (ℓ)	1.5R, 1.8R, 2.1R, 2.4R, 2.7R, 3.0R 3.3R, 3.6R, 3.9R, 4.2R, 4.5R

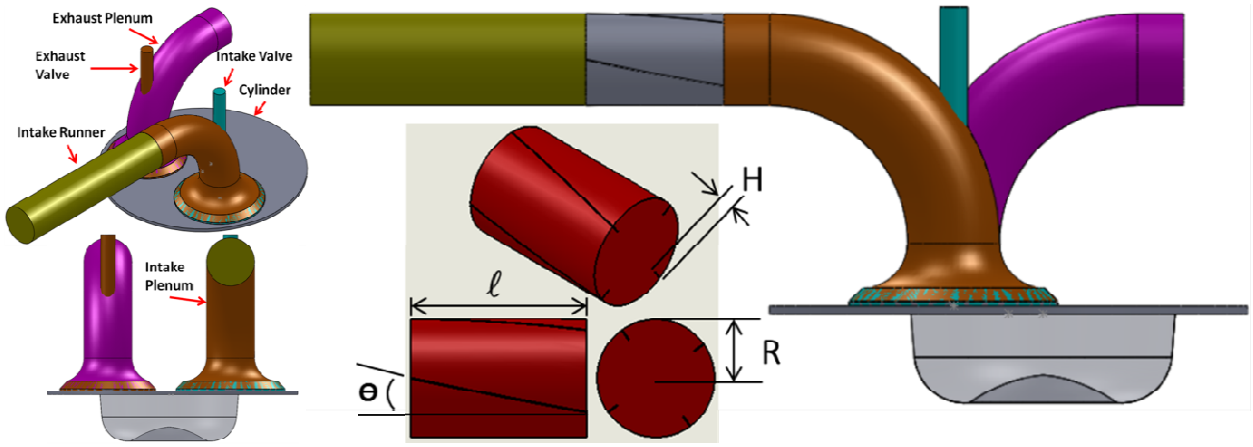

Fig.1: (a) Simulation model (0.00R); (b) Sample design of 4 vanes GVSTD and it assembly to the model.

Results and Discussion

The purpose of this study was to improve the in-cylinder air flow characteristics to improve the evaporation and mixing processes of HVF fuel in IC engines and hence improve the performance of HVF powered CI engines. Three parameters were measured to analyze the air flow characteristics of the models. These parameters are as follows; in-cylinder pressure, TKE and velocity. High in-cylinder pressure reduces the injected fuel penetration length and expands the cone angle allowing more fuel to be exposed to the air. High turbulence kinetic energy causes the molecular structure of the high viscous fuel to break up. Breaking the molecular chemical chain also helps the fuel to mix with the air. High in-cylinder air velocity also helps accelerate the mixing process, particularly because HVF fuels have higher densities generally than conventional petro-diesel. The mixing process needs to be completed during the ignition delay period however the fuel is injected continually until part way into the expansion stroke [5]. Based on Table 1(a), Start of Injection (SOI) occurs at 346°CA, hence this study analyzes the result of in-cylinder pressure, TKE and velocity from 341°CA (5°CA before SOI) to 365°CA (5°CA after TDC) to cover the complete injection period.

In-cylinder Pressure. Fig. 2 represents the maximum in-cylinder pressure of the 11 GVSTD models compared when with the base model. It is evident that the pressure does not share a directly linear relationship with vane length. A similar pattern was observed by P Miles [11] when studying the effect of swirl on combustion at varied levels of throttle. P Miles found using a water-cooled pressure transducer (Kistler 6043A) that the highest pressure was recorded at low throttle, the second highest pressure at high throttle and the lowest pressure at medium throttle. The results acquired are consistent with the results of P Miles and therefore the validity of the data is verified. According to fig. 2, the 3.6R model produced the highest pressure, followed by 3.9R and 3.0R models. These are the only GVSTD models which displayed an improvement over the base model 0.0R. This indicates that 3.0R, 3.6R and 3.9R were successful in drawing a larger volume of air smoothly into the cylinder. The pressure results therefore verify that the GVSTD does improve in-cylinder air characteristics.

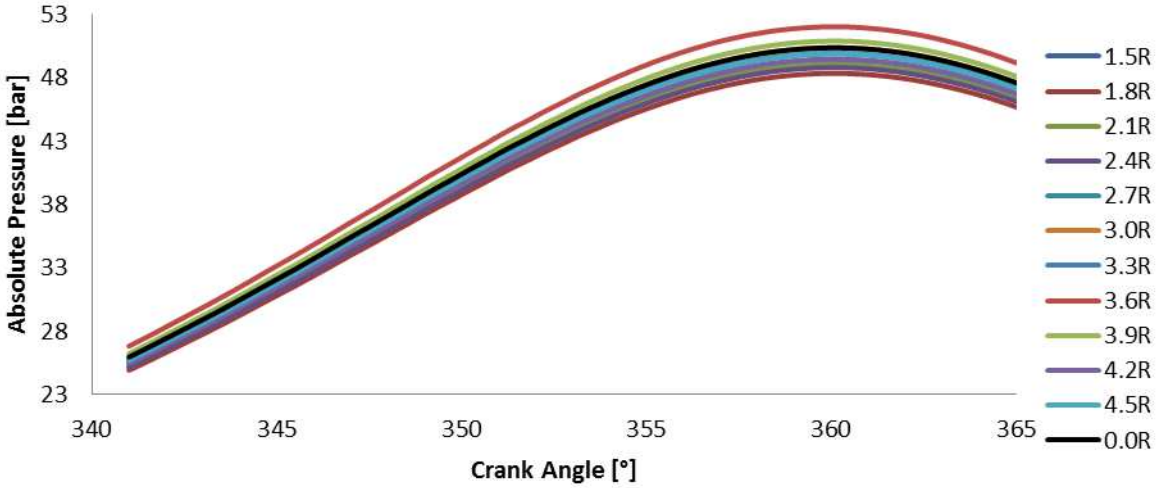

Fig.2: Maximum in-cylinder pressure from 341°CA to 365°CA for various GVSTD lengths.

In-cylinder TKE. Generally, the turbulence kinetic energy reduces when the piston approaches the TDC (Top Dead Centre) according to Payri et al [12]. Payri et al found by the using laser Doppler velocimetry on a diesel engine that the simulation results of their PISO algorithm were valid and accurate. The Payri et al research results are also consistent with the results shown in Fig 3. The only significant improvement in TKE was produced by the 3.9R GVSTD model which showed a significant improvement over the base model analysis throughout the entire range of analysis (341°CA to 365°CA). The 3.6R model produced a lower TKE before 350°CA, however after 350°CA afterwards. The 3.0R model also showed an improvement over the base model data. These results verify that a correctly configured GVSTD may improve the in-cylinder turbulence kinetic energy.

In-cylinder Velocity. The velocity profile developed by GVSTD models as compared to the base model are detailed in Fig. 4. Most of the GVSTD models show an improvement in velocity over the base model (0.0R). The 3.9R and 3.6R GVSTD models were found to produce the most significant improvement of in-cylinder velocity through the range of analysis (341-365°CA). These results confirm that the use of a GVSTD may improve the in-cylinder velocity and hence accelerate the mixing process to improve HVF powered engine performance.

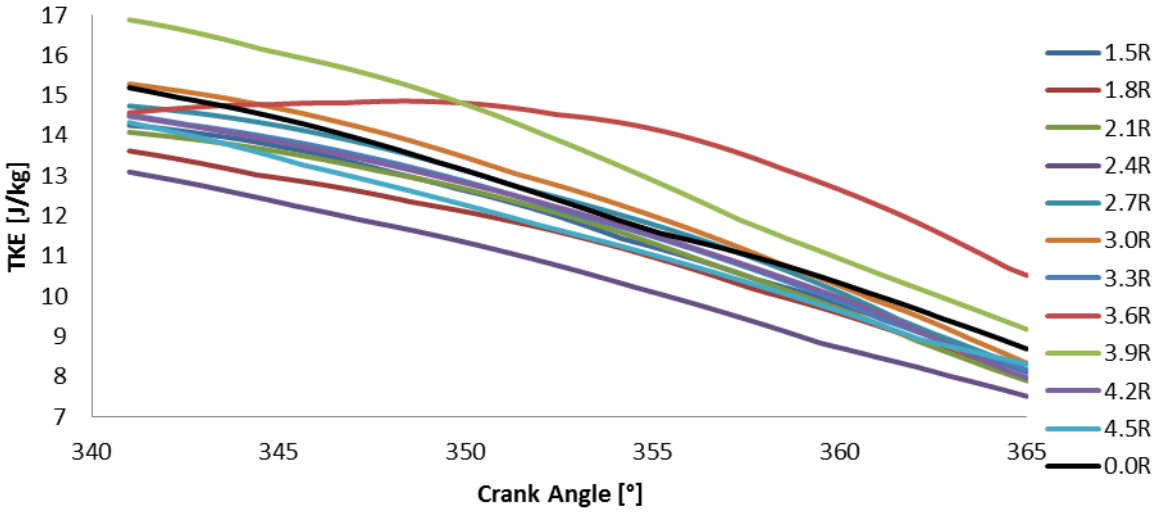

Fig.3: Maximum in-cylinder TKE from 341°CA to 365°CA for various GVSTD lengths.

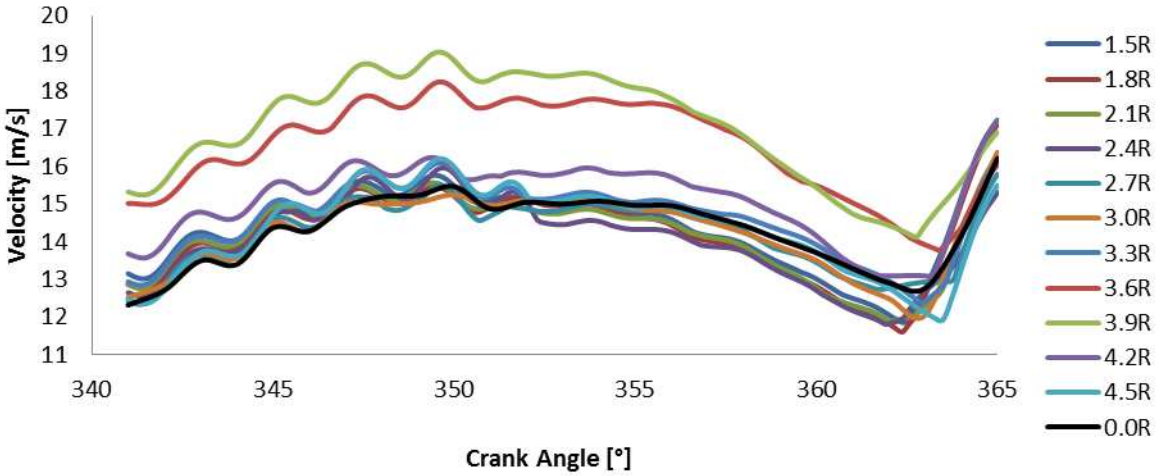

Fig.4: Maximum in-cylinder velocity from 341°CA to 365°CA for various GVSTD lengths.

Optimize Vane Length. Based on the results of in-cylinder pressure, TKE and velocity above, it is evident that the use of a GVSTD can improve CI engine performance when fuelled by a HVF provided the parameters of the GVSTD design are configured correctly. The 3.9R model showed the greatest improvement for both TKE and velocity and the second highest improvement for in-cylinder pressure (3.6R being the highest). Therefore, to optimize in-cylinder pressure, velocity and TKE the vane length should be between 3.6 to 3.9 times the intake radius, for the given constrained parameters detailed in Table 1(b).

Conclusions

Through environmental issues and the depletion of crude oil reserves a need for an alternative fuel to power internal combustion (IC) engines has been developed. Vegetable oil, waste cooking oil and biodiesel are considered to be good supplements or alternative to conventional petro-diesel. These fuels (referred to as Higher Viscosity Fuels, HVFs) are renewable and environmentally sustainable. They can also be used in currently available diesel (CI) engines with minimal engine modification necessary. However, their high viscosity property leads to the reduction of performance when used in diesel engines because of a reduced ability of the in-cylinder air-fuel mixing and evaporative processes. A possible solution to this problem is by improving the in-cylinder air characteristic. This can be done through the use of a Guide Vane Swirl and Tumble Device (GVSTD), installed ahead of the intake runner. There are four parameters of the GVSTD which must be considered when optimizing its effectiveness. These are; vane height, vane length, vane angle and the number

of vanes. For the purpose of this study, the vane height, vane angle and the number of vanes were maintained constant while the vane length was the variable. The in-cylinder flow under motored engine conditions was studied using ANSYS-CFX for the base model and 11 GVSTD models. The vane lengths were varied 1.5 to 4.5 times the radius of intake runner (R) in 0.3R increments. Based on the results of maximum in-cylinder pressure, TKE and velocity, it is concluded that the optimum vane length for a GVSTD set up with four vanes with 35° twist angles and a vane height of 0.2R is between 3.6 to 3.9 times the radius of the intake runner (R). That is the GVSTD models found to improve the in-cylinder air characteristics most effectively were the 3.6R and 3.9R models.

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