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Research Article

The Experimental and Simulations Effect of Air Swirler on Pollutants from Biodiesel Combustion

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Abstract: In the present study the effect of air swirl on the combustion characteristics and pollutant emission of biodiesel B5, B10 and gasoil combustion is studied. The experiments are carried out on an axisymmetric cylindrical combustion chamber. Numerical investigation is conducted using fluent computer code. The RNG, k-ε model is used for the modelling of the turbulence phenomena in the combustion chamber .The eddy dissipation model is used for the simulation of transport combustion. The experimental and numerical result show that the exhaust gas temperature, the levels of NO_x and CO_2 emission increase with increase of swirl number and then decrease. The CO emission declines with increase of swirl number. The numerical and experimental results are in good agreement.

Keywords: Biodiesel, combustion, pollutant emission, simulation

INTRODUCTION

Industrial development and social growth and as a result steep rise for the demand of fossil fuels in one hand and on the other hand pollutant emission of petroleum-based fuels and its effects on environment has led to numerous investigation on alternative fuels which can be produced from local resources within the country. Biofuels are a broad range of fuels which are derived from biomass. The term covers solid biomass, liquid fuels and various biogases including charcoal, vegetable oil, bioethers, biodiesel, syngases, etc. Biodiesel refers to mono alkyl esters of long-chain fatty acids derived from the transesterification of vegetable oil or animal fat feedstock, for use in liquid burners and diesel engines as fuel (Panwar *et al*., 2010; Skoglund *et al*., 2010). A by-product of the transesterification process is the production of glycerol which can be used in pharmaceutical and personal care applications. Properties of biodiesel are similar to common diesel fuel. The main difference between biodiesel and diesel fuel is oxygen content, which is biodiesel contains 10-12 weight percentage oxygen which has improved its performance attributes such as increased cetane number and high fuel lubricating value. However, the calorific value of biodiesel is lower than regular diesel fuel. Biodiesel have negligible sulfur and ash content, so sulfur dioxide emission and toxic pollutants of biodiesel is less than diesel fuel. Many researches have been carried out on biodiesel and its characteristics. The behavior of biodiesel in internal combustion engines is well documented in the literatures (Senatore *et al*., 2000; Roska *et al*., 2005; Agarwal, 2007; Shi *et al*., 2005, 2006; Sharp *et al*., 2000, 2005; Lapuerta *et al*., 2008; Monyem *et al*., 2001; Nabi *et al*., 2006; Laforgia and Ardito, 1995), but a few studies are conducted on the behavior of biodiesel in liquid burners and furnaces. Furthermore, the effects of different parameters such as air swirling flow on biodiesel combustion is not studied completely. Swirling flows are applied in a wide range of application both non-reacting and reacting system (Laforgia and Ardito, 1995).

In combustion systems, it is used in various systems such as industrial furnaces, utility burners, gas turbines, internal combustion engines and many other practical heating devices, in order to enhance mixing and improve combustion and its characteristics (Lilley, 1977; Syred and Beer, 1974). Swirling flows affect flame shape, flame size, stability and combustion intensity by formation of secondary recirculating flows (Chen and Driscoll, 1988). A study by Krishna (2003) examined the effect of replacing heating oil with biodiesel blends in residential heating equipment and commercial boilers. Here, CO emissions for blends of soy methyl ester with No. 2 fuel oil were found to be comparable to that of the fuel oil at fixed fuel pump pressure and at various flue gas oxygen levels. Most significantly, NOx levels reduced as the percentage of biodiesel in the fuel blends was raised. Hoon and Suyin (2010) evaluated levels of exhaust species from the

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Fig. 1: Laboratory combustion chamber

Table 1: Properties of biodiesel and diesel fuel

Properties	Unit	Standard (ASTM)	Gas oil	B20
Density	g/ cm^3	D4052	0.815	0.849
Viscosity	Cst	D445	2.45	3.01
Low heating value	MJ/kg	D240	42.5	41.2
Cetane number	-	D613	57.3	59.6
Flammability point	°C	D93	61	72

combustion of Palm Oil Methyl Ester (POME) and its blends with No. 2 diesel in a non-pressurized, water-cooled combustion chamber. They explored the correlations between emission species and fuel pumping pressures over a range of equivalence ratios. Their results indicated an improvement in combustion and the potential use of palm oil biodiesels in small-scale liquid fuel burners. Datta and Som (1999) investigated combustion and emission characteristics in a gas turbine combustor at different pressure and swirl conditions. They reported that an increase in swirl number reduces the NO_x emission level at all combustor pressures. However, though at lower pressure and increase in swirl number decreases combustion efficiency, the trend is exactly the reverse at higher pressure. The effect of swirl on combustion dynamics in a lean-premixed swirl-stabilized combustor is studied by Huang and Yang (2009). They found out that a high swirl number tends to increase the turbulence intensity and the flame speed and consequently shorten the flame length. However, excessive swirl often causes the central recirculating flow to enter into the inlet annulus and leads to the occurrence of flame flashback. Bashirnezhad *et al*. (2007) studies the effect of fuel angles and air swirling flow on soot formation. They showed that the maximum temperature of flame has increased with increase of swirl number and remained constant with further increase of swirl number. The aim of this study is measuring regulated emissions such as CO, CO_2, NO_x and flame temperature from boiler fueled with biodiesel and gasoil at different swirl number.

Experimental setup: The laboratory furnace which is used in this research includes a horizontal cylinder to the length of 170 cm and diameter of 50 cm. On the rims of furnace some orifices in different spaces from burner nozzle have been made for measuring temperature and sampling combustion gases. The liquid burner is a pressure jet oil burner with 400 KW maximum power rating. The fuel is supplied to the nozzle at pressure of 12 bars. The fuel and air flow rate are adjustable using the oil pump and the burner air valve, respectively. A variable swirl burner provides near-burner zone high mixing rates of air and fuel. Fuel is injected to the furnace through a 60° hollow-cone nozzle. A K Type thermocouple, which stands high temperatures, is used to provide temperature measurements within the furnace. The thermocouple is directly coupled with a voltmeter which shows the temperature in Celsius. Figure 1 shows the laboratory combustion chamber. Table 1 compares the properties of diesel fuel and biodiesel that is used as fuel.

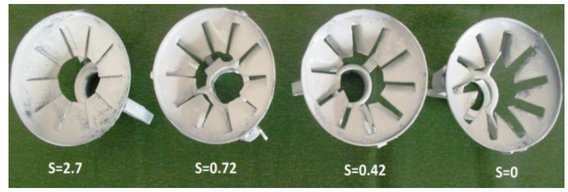

Fig. 2: Swirler

In order to produce swirling flow, five air swirlers having different vane angles are applied. They are made from mild steel. The inner diameter of air swirlers is 20 mm and their outer diameter is 60mm. The vane angles of air swirlers are 0°, 30°, 45°, 60° and 75° that their swirl number are 0, 0.42, 0.72, 1.25 and 2.7 respectively. Figure 2 demonstrates the swirlers. All of the measurements are made after stabilization of furnace temperature. During the experiments, the air and input fuel temperatures have been controlled and maintained. The sampling device has been placed in the stack for analyzing exhaust gases, on the 160cm from furnace vent. The gas stream produced from combustion like CO, CO_2 and NO_x is registered each 5 minutes using a Testo 350 XL for analyzing gas. Table 2 demonstrates a list of instruments and their specifications.

Numerical simulation: The continuity, momentum and energy equations in cylindrical coordinates can be expressed in the form of general form of governing equation:

$$\frac{\partial}{\partial X}(\rho U\varphi)+\frac{1}{r}\frac{\partial}{\partial r}(r\rho V\varphi)+\frac{1}{r}\frac{\partial}{\partial \theta}(\rho W\varphi)= \frac{\partial}{\partial x}\left(\Gamma_{\varphi}\frac{\partial \varphi}{\partial X}\right)+\frac{1}{r}\frac{\partial}{\partial r}(r\Gamma_{\varphi}\frac{\partial \varphi}{\partial r})+\frac{1}{r}\frac{\partial}{\partial \theta}(\Gamma_{\varphi}\frac{\partial \varphi}{\partial \theta})+S_{\varphi} \quad (1)$$

where, φ is a dependent variable and can be mass, momentum, Turbulence kinetic energy and its dissipation rate and enthalpy. Γ_{φ} is the diffusion coefficient and S_{φ} is the source term.

Swirl flow affects the combustion and the characteristics of flame by enhancing the mixing of fuel

Table 2: List of measurement instruments and their specifications

Instrument	Range	Resolution	Accuracy (%)
Hotek AM 4206vanemometer	0.4-25 m/s	0.1 m/s	±2
Satronic SOG960 oil flow meter	1-40 lit/h	± 0.01 lit/h	±2.5
K- type thermocouple for exhaust gas temperature	0-1100°C	± 1°C	±0.75
O_2 sensor	0-25%	± 0.1 %	±0.2
CO_2 sensor	0-20%	± 0.1 %	±2
CO sensor	0-10,000 ppm	±1 ppm	±2
SO_2 sensor	0-5000 ppm	±1 ppm	±2
NO sensor	0-3000 ppm	±1 ppm	±2
NO_2 sensor	0- 500 ppm	± 0.1 ppm	±2

and air. These affects are depending on the intensity of swirl which is shown with a non-dimensional parameter called swirl number S. Swirl number is defined as the axial flux of swirl momentum divided by axial flux of axial momentum, times the equivalent nozzle radius (Gupta *et al*., 1984):

$$S = \frac{G_\varphi}{G_x \frac{D}{2}} \tag{2}$$

where,

$$G_\varphi = \int_0^\infty (\rho u_x u_\varphi) r^2 dr \tag{3}$$

$$G_x = \int_0^\infty \left(\rho u_x^2 + (p - p_\infty)\right) r dr \tag{4}$$

NO_x Post-processing: In the present study, thermal-NO_x and prompt NO_x is considered which their modeling is carried out in the post-processing stage. A single transport equation for mean NO mass fraction with a source term is solved after obtaining converged solution for the flow and mixing field through the turbulent flow calculations:

$$\rho \frac{\partial Y_{NO}}{\partial t} + \rho u_i \frac{\partial Y_{NO}}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\rho D \frac{\partial Y_{NO}}{\partial x_i}\right) + S_{NO} \tag{5}$$

The kinetics of the thermal NOx formation rate is much slower than the main hydrocarbon oxidation rate and most of the thermal NO_x is formed after completion of combustion. Therefore, the thermal NO formation process can often be decoupled from the main combustion reaction mechanism and the NO formation rate can be calculated by assuming equilibration or partial equilibration of the combustion reactions.

The thermal NO_x is formed by the oxidation of atmospheric nitrogen at high temperatures and prompt NO_x is formed by reactions of intermediate species at the flame front (Ilbas *et al*., 2005). The principal reactions governing the formation of thermal NOx from molecular nitrogen are given by the extended Zeldovich mechanism (Zeldovich, 1947):

$$\begin{gathered} O + N_2 \xleftrightarrow{k_{\pm1}} NO + N \\ N + O_2 \xleftrightarrow{k_{\pm2}} NO + N \\ N + OH \xleftrightarrow{k_{\pm3}} NO + H \end{gathered} \tag{6}$$

$k1$, $k2$ and $k3$ are the rate constants for the forward reactions 11-13 respectively and k-1, k-2 and k-3 are the corresponding reverse rates. The overall thermal NO formation rate can be calculated as:

$$\frac{d[NO]}{dt} = 2k_{+1}[O][N_2]\frac{\left(1 - \frac{k_{-1}k_{-2}[NO]^2}{k_{+1}[N_2]k_{+2}[O_2]}\right)}{\left(1 + \frac{k_{-1}[NO]}{k_{+2}[O_2] + k_{+3}[OH]}\right)} \tag{7}$$

The concentration of O and OH is given by:

$$[O] = 36.64T^{1/2}[O_2]^{1/2}\exp\left(\frac{-27123}{T}\right)$$

$$[OH] = 2129T^{-0.57}\exp\left(\frac{-4595}{T}\right)[O]^{1/2}[H_2O]^{1/2} \tag{8}$$

The prompt NO_x formation is significant in most hydrocarbon fuel combustion conditions and the prompt NO_x route is generally accepted as:

$$\begin{gathered} CH + N \longleftrightarrow HCN + N \\ N + O_2 \longleftrightarrow NO + N \\ HCN + OH \longleftrightarrow CN + H_2O \\ CN + O_2 \longleftrightarrow NO + CO \end{gathered} \tag{9}$$

The prompt NO formation rate is calculated from the (De Soete, 1975) global model as:

$$\frac{d[NO]}{dt} = q \times 1.2 \times 10^7 \times \left(\frac{RT}{P}\right)^{a+1} \times \tag{10}$$

$$[Fuel][O_2]^a[N_2] \times \exp\left(\frac{-E_a}{RT}\right) \tag{11}$$

The NO source term due to thermal NO_x and prompt NO_x mechanism is:

$$S_{NO,th} = M_{NO} \frac{d[NO]}{dt} \tag{12}$$

where, M_{NO} is the molecular weight of NO and d[NO]/dt is calculated (computed) from equation 7 and 11.

Combustion modeling: The eddy dissipation combustion model which is based on the study of Magnussen and Hjertager (1976) is derived to simulate combustion. The reaction chemistry is a simple infinitely fast one step global irreversible reaction. At first fuel droplet changes to gaseous phase then combustion starts. Vaporization starts when the temperature of the droplet reaches the vaporization temperature and continues until the droplet reaches the boiling point or until the droplet's volatile fraction is completely consumed (Magnussen and Hjertager, 1976). A one step chemical reaction between gasoil and biodiesel with air is

$$C_{16}H_{29} + 23.25O_2 \rightarrow 16CO_2 + 14.5H_2O \tag{13}$$

$$C_{21}H_{38}O_2 + 29.5(O_2 + 3.76N_2) \rightarrow 21CO_2 + 19H_2O + 110.9N_2 \tag{14}$$

Computational procedure: The Fluent computer code is used to model a 2D steady-state simulation of physical domain which is considered axisymmetric due to axial symmetry of the system. The numerical simulation is performed using a quadrilateral and structured grid of mesh elements, with high resolution in the region close to the inlet. The domain Fig. 3 shows the mesh generation with 320*130 control volumes in a cylindrical coordinate system. Simulations with finer grids show that the quality of prediction is not improved by enhancing the number of cells used. The pressure based solver is used with SIMPLE procedure. Standard algorithm is applied for pressure interpolation. Turbulence is modeled, using the standard k-ε model.

RESULTS AND DISCUSSION

Experimental and numerical study on the effect of air swirl on combustion characteristics and pollutant emission of biodiesel B5, B10 and gasoil are investigated. Results indicate an enhancement in combustion features and pollutant emission with use of air swirl for both biodiesel and gasoil combustion. Figure 4 shows the comparison of experimental data of this study.

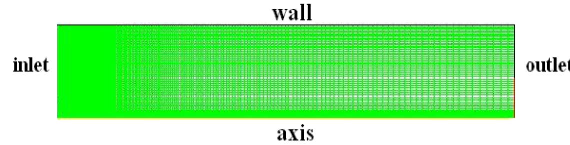

Fig. 3: Grid of mesh

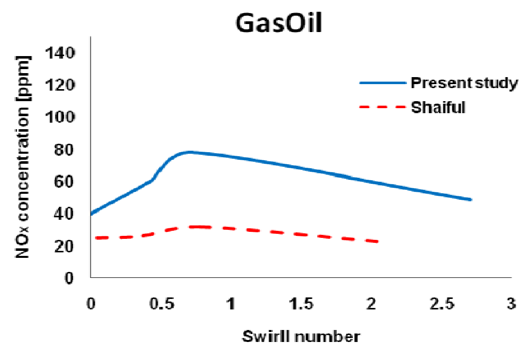

Fig. 4: Comparison of experimental results (shaiful *et al*.; 2005)

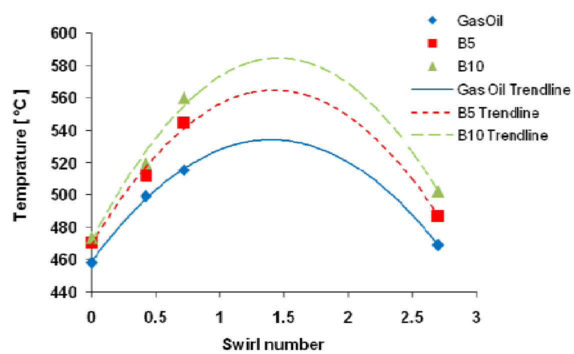

Fig. 5: Effect of swirl number on the exhaust gas temperature

Figure 5 presents the effect of swirl number on the temperature of exhaust gas. The exhaust gas temperature is increased with increase of swirl number from 0 to 0.72 then it is declined with rise of swirl number from 0.72 to 2.7. The increase of swirl number from 0 to 0.72 has enhanced the mixing of fuel and air. As a result, the combustion efficiency is improved and the temperature is increased.

The effect of swirl number on the NO_x emission is demonstrated in Fig. 6. The level of NO_x emission is increased with increase of swirl number from 0 to 0.72 then it is decreased. The trend of NO_x emission and temperature are similar that indicates the effect of temperature on NO_x formation; moreover, it shows that the dominant reaction mechanism of NO_x formation at high temperature is zeladovich thermal mechanism. It can be seen from Fig. 6 that the level of NO_x emission is grown in biodiesel B5 and B10 combustion in contrast with gasoil. Oxygen content of biodiesel and

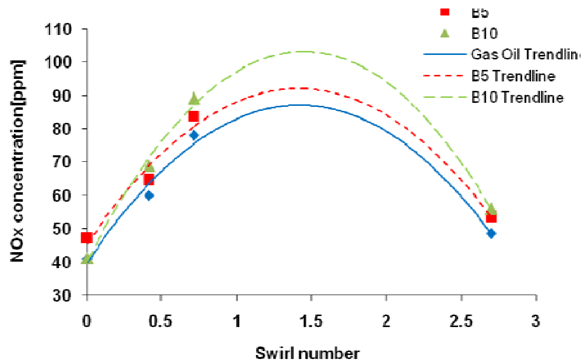

Fig. 6: Effect of swirl number on NO_x emission

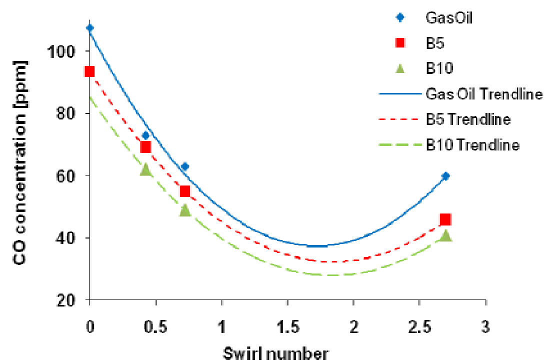

Fig. 7: Effect of swirl number on CO emission

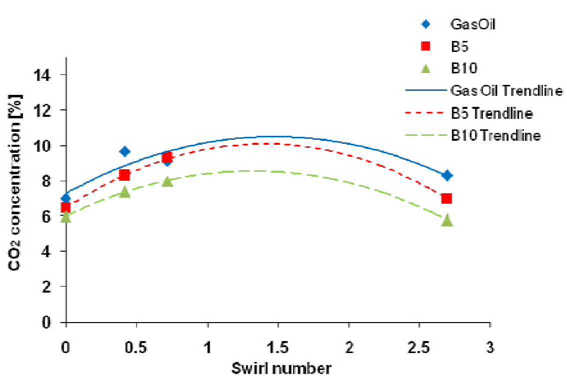

Fig. 8: Effect of swirl number on CO_2 emission

higher combustion temperature of biodiesel are responsible for this growth of level emission.

Figure 7 depicts the effect of swirl number on the level of CO emission. CO emission is abated with increase of swirl number because of combustion improvement. CO concentration is decreased from 110 ppm at swirl number 0 to 50 ppm at swirl number 2.7 in gasoil combustion. The enhancement of combustion has provided the sufficient energy for oxidazation of CO to CO_2, so the level of CO is declined.

Figure 8 shows the effect of swirl number on CO_2 emission. CO_2 emission is increased with improvement on combustion due to increase of swirl number from 0

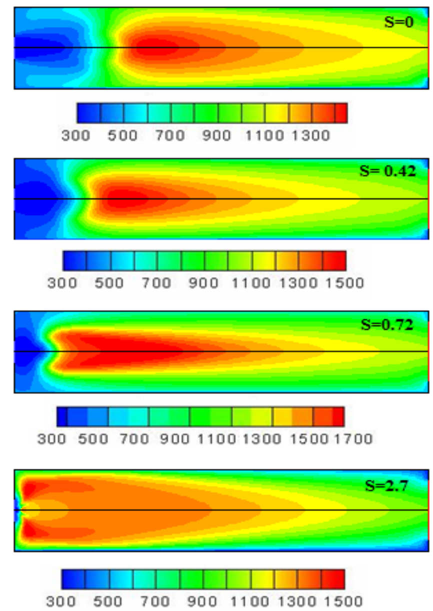

Fig. 9: Temperature contour through the combustion chamber

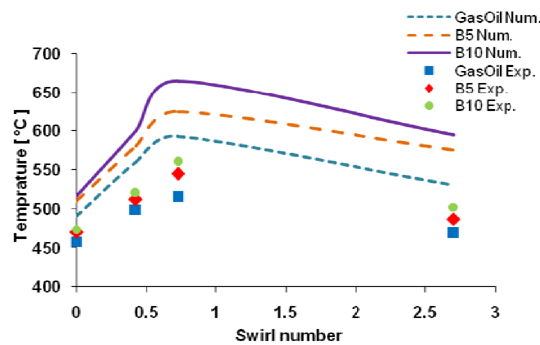

Fig. 10: Comparison of numerical and experimental data for exhaust gas temperature

to 0.72 and then it is decreased from swirl number 0.72 to 2.7. As it can be seen, the level of CO_2 emission in combustion of biodiesel B5 and B10 is not changed obviously in comparison with gasoil combustion.

In Fig. 9 the temperature contour of numerical simulation is shown for excess air ratio 1.25. As it demonstrates, the maximum temperature of flame is increased from 1300 K for swirl number 0 to 1700 K for swirl number 0.72 and then it is decreased to 1500K for swirl number 2.7. The Fig. 9 also shows that the region of maximum flame temperature is tended to the inlet of combustion chamber with increase of swirl number.

Figure 10 depicts the comparison of numerical and experimental results for the effect of swirl number on the exhaust gas temperature. The comparison shows good agreement for combustion of biodiesel B5, B10 and gasoil. The Fig. 10 shows a little discrepancy between numerical data and experimental results due to the combustion model which is used in simulation. The

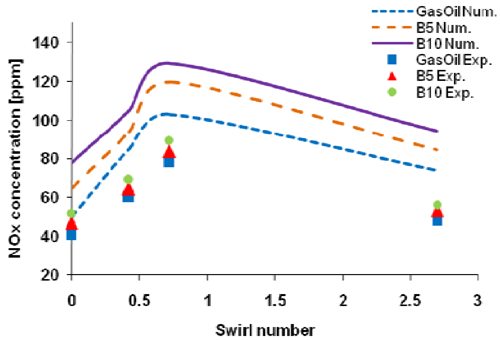

Fig. 11: Comparison of numerical and experimental data for NO_x emission

eddy dissipation combustion model uses a reaction chemistry with a simple infinitely fast one step global irreversible reaction.

In Fig. 11 the comparison of numerical and experimental results for the level of NO_x emission is illustrated. As it can be seen the results are in good agreement.

CONCLUSION

An experimental investigation on the effect of air swirl on combustion characteristic and pollutant emission of biodiesel B5, B10 and gasoil is carried out. Based on the presented results, the following conclusions may be drawn:

- Exhaust gas temperature is increased with increase of swirl number due to improvement of combustion from non-swirl air flow to swirl flow with swirl number 0.72.
- The levels of NO_x and CO_2 emission has raised with increase of swirl number from swirl number 0 to 0.72 then are abated.
- The region of maximum flame temperature is tended to inlet of combustion chamber with increase of swirl number.
- Experimental and numerical results are in good agreement.

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