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Effect of Swirl on Temperature Decay Function in Straight Blade Liquid Fuel Swirl Burner

Olanrewaju Miracle Oyewola[1*], Ademola Samuel Akinwonmi[2], Olusegun Olufemi Ajide[3], Tajudeen Ogunniyi Abiola Salau[3]

[1] School of Mechanical Engineering, Fiji National University, Suva 67901, Fiji
[2] Department of Mechanical Engineering. Ajayi Crowther University, Oyo 200284, Nigeria
[3] Department of Mechanical Engineering, University of Ibadan, Ibadan 200132, Nigeria

Corresponding Author Email: olanrewaju.oyewola@fnu.ac.fj

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ABSTRACT

The need to shield the surroundings from fire or combustion generated pollutants has led to substantial demand for perk up burner design with better performance. In this study, the geometry of a liquid fuel burner has been modified by introduction of straight edge blade swirler and thereafter, measurement using chromium-zinc thermocouple of radial and axial temperature distributions. The straight blade swirl generator consists of 6 number of blades at angles 20°, 30°, 40°, 50° and 60°, respectively was fired by conventional diesel in an experimental model liquid fuel swirl burner. The highest axial temperature of combustion without and with swirler was 930℃ and 1121℃, respectively, while the highest radial temperature without and with swirler was 942℃ and 1130℃, respectively. The achieved 21% performance improvement suggests that burners with swirl have varied higher flame temperature and combustion intensity than their counterpart without swirl. The outcome of this study has revealed that higher agitation of the swirl significantly affected the thermal profile and this subsequently led to high combustion intensity. The changes can be attributed to turbulence being provoked at selected angles of swirl blade. The effect is enhanced as the angle of swirl blade increases, howbeit, until a threshold is reached.

1. INTRODUCTION

The enormous role of combustion technology in the present century as an agent of industrialization cannot be over emphasized. Bilger [1] described combustion as a process of transforming primary energy into useful secondary energy such as heating, mechanical and electrical power. With the aid of burner systems, combustion involves rapid oxidation and release of large amounts of energy at high temperatures. Burners are used as starters for boilers, furnaces, heaters, kilns, ovens, and dryers for various industrial heating, cooling, power generation and applications that involves separation of particulate emissions in cyclones [2-6] in chemical, iron and steel, glass, food and beverage, pulp and paper, mining and host of other processing industries. However, the ever-increasing global demand for reduction in emissions of Greenhouse Gases (GHGs), enhanced thermal efficiency and optimum energy saving conditions in industrial combustion process are challenging tasks attracting attention of researchers [7-13].

Consequently, the quest for development of low GHGs emission combustion technologies has necessitated the drive for innovative research to accomplish the desire [14]. For example, in combustion systems, a strong injection application of swirl air and fuel is used as an aid to stabilize the combustion process such as the application on the gasoline engine, diesel engine, gas turbines, industrial furnaces and other equipment that produce hot gases [15]. Yilmaz [16] reported that mixing of fuel and swirl air in the combustion devices had shown strong effect on combustion characteristics and emission behaviours of fuel-fired systems. This is not surprising as [17] reported that swirl burner was very usable device especially in combustion applications such as industrial furnaces and boilers or gas turbines.

Laudable efforts had been made with respect to enhanced combustion process using various swirl burner system technologies [18-26]. Although studies on Liquid Fuel Swirl Burner (LFSB) are generally limited, the beneficial application of liquid fuel may be the reason for recent research efforts in this regard. For instance, LFSB is becoming more favoured as a result of soar combustion intensity with regenerative and low emission characteristics [10]. Investigative studies on factors (such as swirl numbers, angles, geometry, temperature, etc.) influencing performance response of LFSB system are gaining prominence. For example, Jugjai et al. [10] examined the combustion characteristic of LFSB taking into consideration the effects of equivalence ratio, thermal input as well as downstream installation of the porous emitter. Their study revealed that optimum optical thickness of the porous emitter of 2.54 yielded significant reduction in NO_x emission. It was reported that the choice of operating conditions and optical thickness of the porous emitter had a very strong influence on control of CO emissions. Ishak and Jaafar [8] carried out a study on the influence of swirl number on the degree of emission control in LFSB system for radial air swirler vane angles (10 to 70°) with 280 mm inside diameter and combustor length of 1000 mm. In comparison with swirl number of 0.046, findings revealed that swirl number of 0.978, 1.427 and 1.911 led to remarkable reduction of CO emissions by 33, 40 and 48%, respectively.

Reductions in NO_x and CO_2 emissions were equally observed to reduce significantly with swirl number more than 0.046. The authors also reported that NO_x emissions of less than 35 ppm were attainable over the range of equivalence ratios employed for all swirlers. The research output of the authors reported herein has provided useful limelight that increase in swirl number is of immense benefit in enhancing the degree of mixing of air and fuel prior to ignition.

Furthermore, Klancisar et al. [27] investigated the influence of swirl flow intensity on the combustion characteristics of a LFSB. The study showed that an increase in swirl number improved the intensity of the recirculation flow in the flame core. This led to reduction of temperatures on the outer flame shell and enhanced NO_x reduction. Although with increase of NO_x in the flame core, the study further revealed that a more efficient thermal profile in the swirl flame burners was achieved with higher swirl strength and core flame temperature. The study carried out by Jeong and Lee [28] showed that as the swirl angle increased, the NO_x and CO emissions were found to decrease as a result of the mixing enhancement and shorter resident time.

Moreover, Nayak et al. [29, 30] showed that under proper combustion conditions, the emission of nitrogen oxides (NO_X) increases and also, carbon monoxide (CO) as well as unburnt hydrocarbons (UHC) decreases. However, under improper combustion conditions, the results obtained were opposite. Meanwhile, Songa et al. [31] reported that combining bluff body as well as doubling secondary air flow velocity of the swirling in order to obtain optimal performance can possibly lead to cleaner and more efficient combustion Further, Fuzesi et al. [32] carried out the numerical simulation of distributed combustion in the absent of air dilution in a novel ultra-low emission turbulent swirl burner. The study revealed that the uniformity in fuel–air mixture was the major reason for the very good flame stability as well as extremely low NO_x emission obtained without significant internal recirculation.

In an attempt to further study emission reduction, De Giorgi et al. [33] conducted experiments in a 300-kW liquid-fueled swirling combustor in order to examine the performance and emission characteristics of a water emulsified fuel under various water contents. They found that NO_x emission reduces as a result of decrease in the gas exhaust temperature in presence of water emulsified fuel. In addition, they found that CO emission reduces relative to the net fuel under leaner conditions as the air flow rate was increased.

Furthermore, the effect air swirl vane angle in the range of 0 to 75° on combustion characteristics of liquid fuel burners was investigated by Pourhoseini et al. [34]. The NO and CO pollutant concentrations of the liquid fuel burner were also evaluated. The study revealed that at an optimum angle 45° for the swirl vane, the average temperature of the flame increases. This in turn led to attainment of maximum combustion efficiency at extremely low CO emission level. It was also demonstrated that large swirl angles substantially decrease NO emission level. Also, Akinyemi and Jianga [35] designed a novel swirl burst injector using the concept of flow blurring injection in swirling atomizing air. Their results indicated very low CO and NO_x emissions especially at the combustor exit and concluded that clean combustion was achieved using straight vegetable oil as fuel. This is not surprising as the result obtained is in agreement with Hussei et al. [36-40] which show that the design of the burner can affect the flame topology and hence the emission levels. Moreover, Sauer et al. [41] examined combustion characteristics of a non-premixed LFSB using tubular flame configuration with condensed fuels in order to develop a theoretical model. Interestingly, at fuels unity Lewis number, the developed model was able to provide qualitative guidelines on the effect of various inlet parameters on flame position and confinement, overall system temperature as well as heat transfer characteristics for a non-premixed swirl-type tubular system. Zhou et al. [42] studied the effects of modifying burner geometry on the response of non-premixed flame. It was found that burners with inlet length of 0.245 m and 0.345 m yielded maximum flame heat release. The obtained flame behavior based on acoustic mode in large-size width and depth, was reported to be of great application in boiler fired system. Hidegh et al. [7] used a test rig with combustion power of 15 kW of a premixed liquid fuel burner equipped with an air blast atomizer to study the relationship that might exist among the chemiluminescent signal, the CO as well as NO_X by modifying the combustion air flow rate, atomizing pressure, vertical alignment of the spectrometer as well as quarl half-cone angle mounted on the burner lip. The findings reported by the authors showed that air-to-fuel equivalence ratio had the most significant effect on the control of NO_X emission. The study also deduced that the correlation coefficients of the intensity ratio of chemiluminescent signals with CO and NO_X could be used for emissions control in LFSB system.

Despite the fact that temperature is quintessential in the control of the performance characteristics of combustion equipment [43, 44] there is paucity of research information that focus on the influence of temperature decay function on LFSB. Therefore, in this paper, the burner geometry of a liquid fuel burner has been modified by introduction of straight swirl generator. The temperature profile of the modified LFSB is investigated with the aim of enhancing performance characteristics of the burner systems.

2. MATERIALS AND METHODS

The experimental model liquid fuel swirl burner used for this research was developed and it consists of a high pressure liquid pump atomizer with swirl before the nozzle operating at a pressure above 10 bar. A single output centrifugal blower powered by 2850 rpm, 0.5hp, 3 phase electric motor with a 2-inch gate valve for varying the air flow-rate was used. The burner is made of mild steel (with density of 7.85 g/cm^3; melting point of 1450℃) but the combustion chamber is made from stainless pipe steel type 304 of thickness 4 mm with dimension 108 mm × 420 mm per modular section. It has five modules; each module has a flange machined with projection that exactly fits with the recess on the adjacent module to prevent leakages. The base module has a hinge which is fastened to the burner body by 1 M10-6H bolt and nut. Each module has ports for measurement probes. The modular combustion chamber enables the monitoring and evaluation of the flame length velocity and pressure drop. The blades/vanes are also made using mild steel welded to the centre core on a rod whose base has been threaded for fastening to the burner with M10-6H nut. Figure 1 shows the schematic arrangement of the developed LFSB (All dimensions in millimetre).

Straight blade swirl generator with 6 numbers of blades at angle 20°, 30°, 40°, 50° and 60°, respectively were used for this study. Conventional diesel was used as fuel and fired in an experimental model liquid fuel swirl burner. The ambient temperature was 35℃ and the combustion temperatures via the six axial ports at distance (d) (= 150, 350, 550, 750 950 1150 mm) from the burner exit were taken using chromium-zinc thermocouple with an effective range of (0-1300°C). Radial measurements of the temperature were also taken from the centre of the chamber in step of 9 mm towards the outer surface where there is direct interaction with the environment. The time taken for each temperature measurement was 5 minutes for stability. The measurements were repeated three times and the uncertainty was ±5%. The burner was fired with swirl generator. In addition, the burner was also fired without swirl generator in order to provide a reference against which the effect of swirl can be assessed.

3. RESULTS AND DISCUSSION

The streamwise evolution of the temperature decay functions in liquid fuel burner without swirl generator for axial and radial temperatures are presented in Figures 2a and 2b, respectively. Similarly, Figures 3 to 7 show the axial and radial temperatures decay functions for liquid fuel burner with 6 blades swirl generator at angles 20°, 30°, 40°, 50° and 60°. respectively. Interestingly, for all cases, temperature decay along the axial distance and the radii distance follows the same trend except for axial temperature with swirler, where temperature increases almost linearly till optimum is reached before starting to decrease in the same manner. It should be noted that temperature decreases radially from the centre of the combustion chamber towards the outside where there is direct interaction with the surroundings. Similarly, temperature decreases along the combustion chamber from port 1 to port 6 in the flame direction with port 1 having the highest temperature in combustion without swirl generator and longer flame length. However, for swirl generators, the temperature increases from port 1 to port 3 which is the peak of combustion intensity with axial distance 550 mm near nozzle but started to decrease in port 4, suggesting that combustion is improved immediately after the burner exit due to proper mixing of fuel and air. This might due to the turbulence created by the swirl blade and however, the effect reduces further downstream. Consequently, flame length seen to be longer in combustion without swirler than in combustion with swirler.

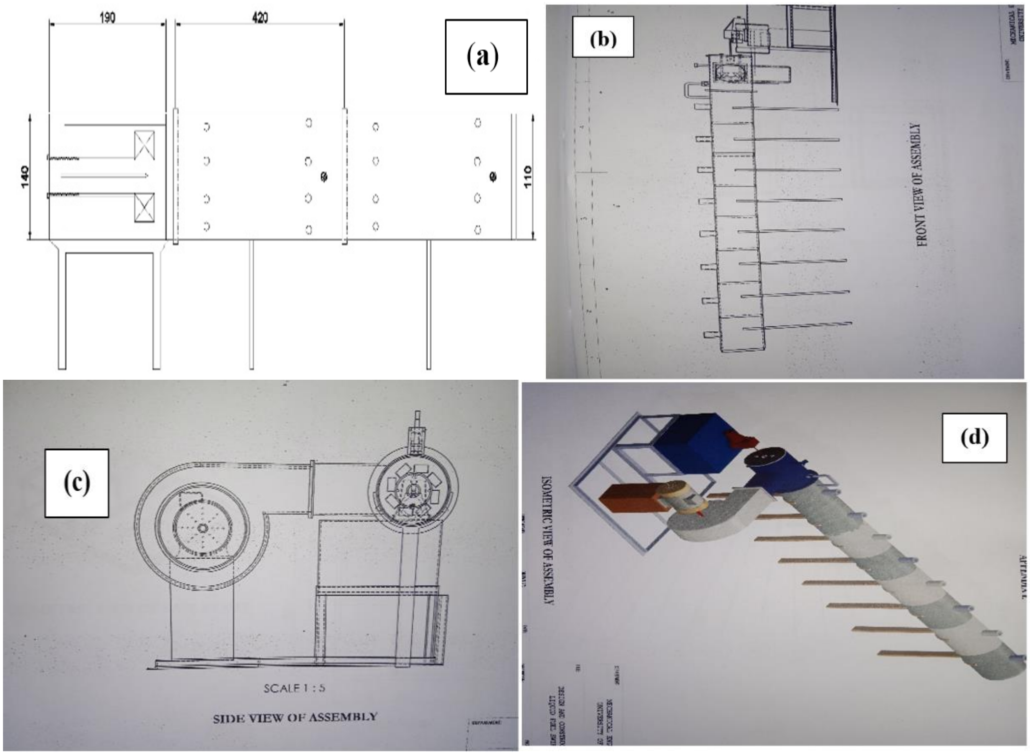
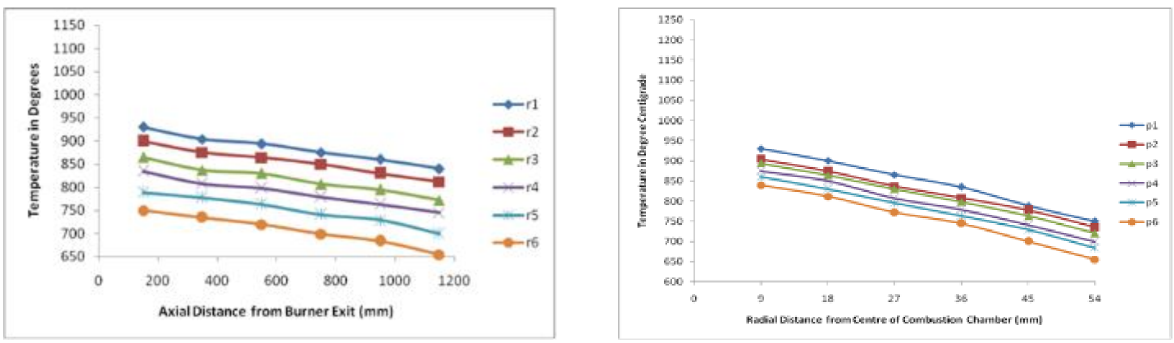
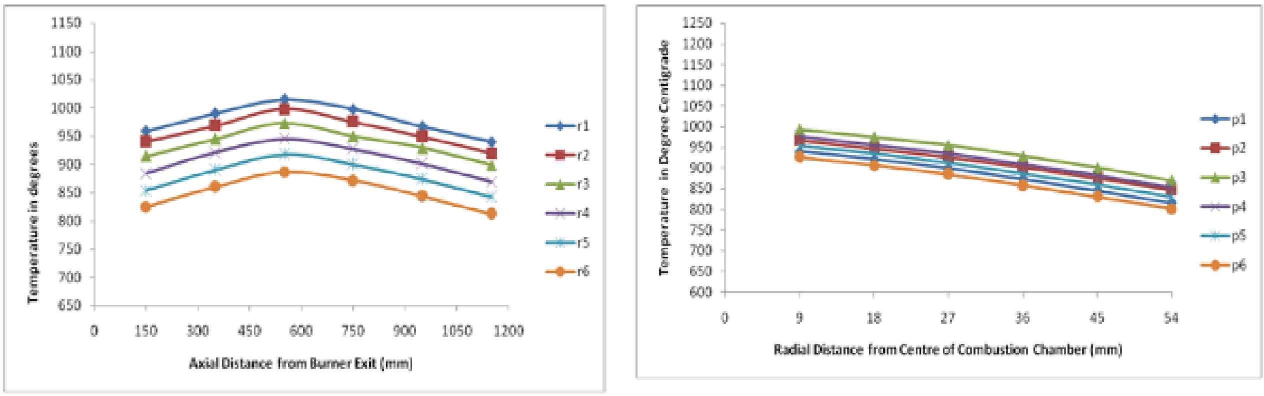


Figure 1. Liquid fuel swirl burner (a) Schematic arrangement (b) Front view (c) Side view (d) Isometric view



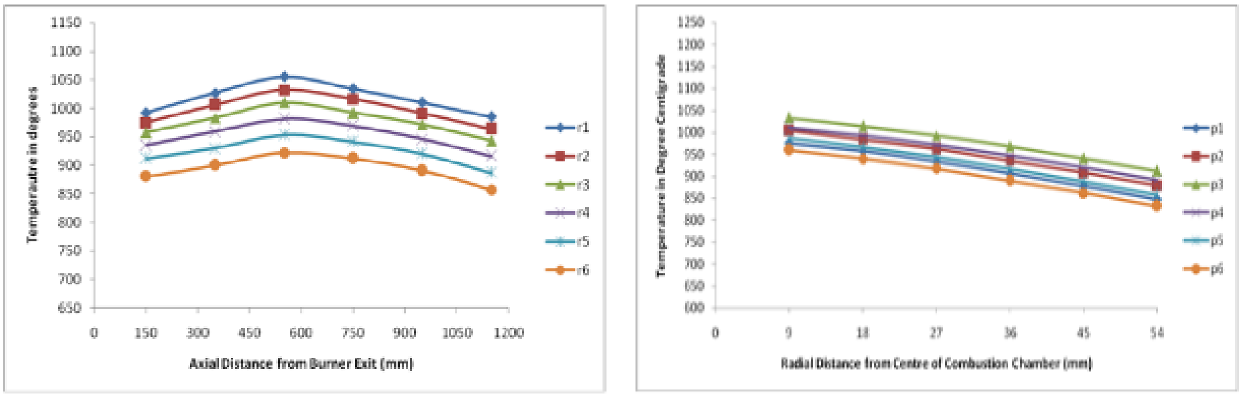
(a) (b)

Figure 2. Distribution of temperature profile of straight blade at swirl angle of 0°: (a) Axial; and (b) Radial



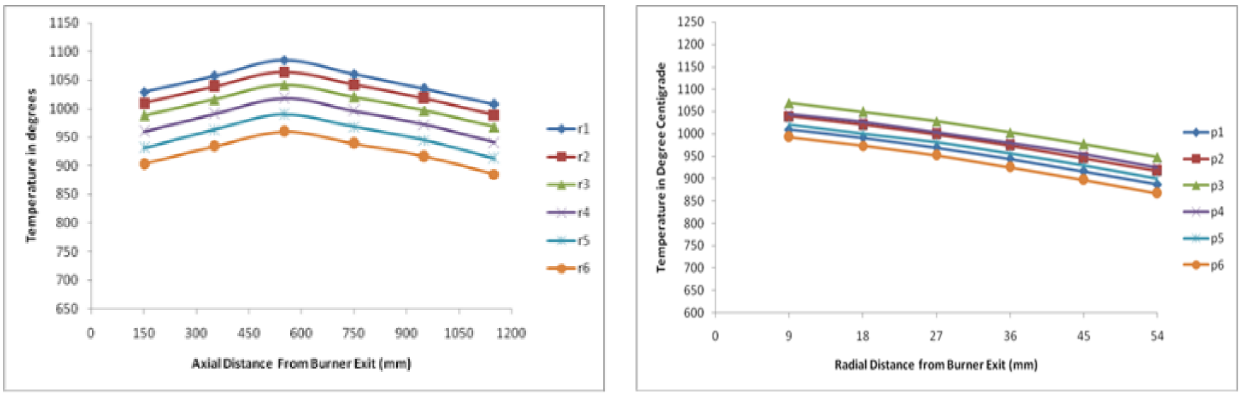
(a) (b)

Figure 3. Distribution of temperature profile of straight blade at swirl angle of 20°: (a) Axial; and (b) Radial



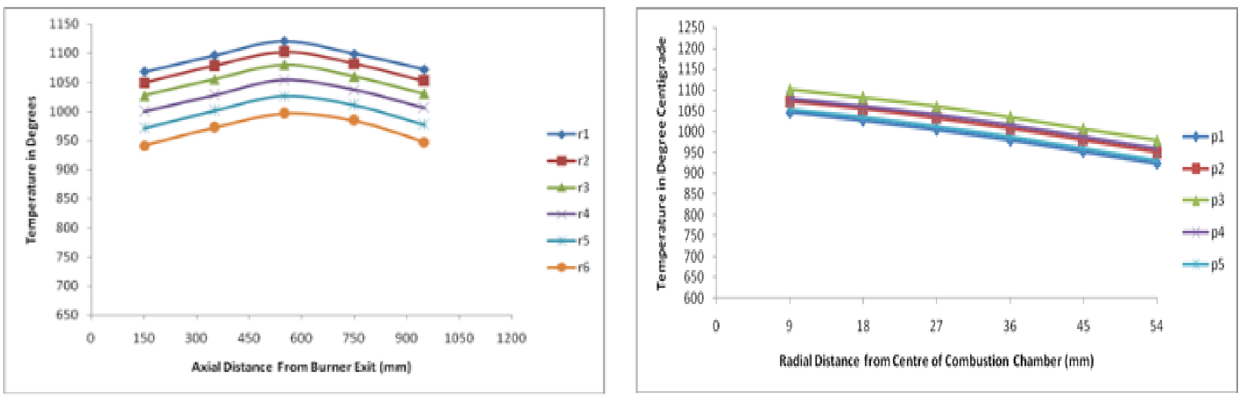
(a) (b)

Figure 4. Distribution of temperature profile of straight blade at swirl angle of 30°: (a) Axial; and (b) Radial



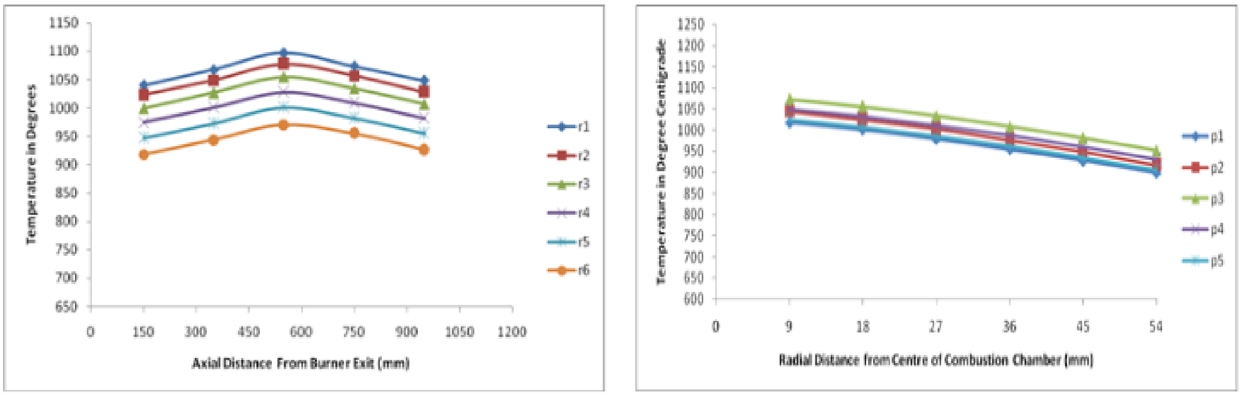
(a) (b)

Figure 5. Distribution of temperature profile of straight blade at swirl angle of 40°: (a) Axial; and (b) Radial



(a) (b)

Figure 6. Distribution of temperature profile of straight blade at swirl angle of 50°: (a) Axial; and (b) Radial



(a) (b)

Figure 7. Distribution of temperature profile of straight blade at swirl angle of 60°: (a) Axial; and (b) Radial

In all Swirl angles, temperature decreases radially from the centre of the combustion chamber towards the outside where there is direct interaction with the surroundings just as combustion without swirler. This is not surprising since for 6 number of blades, there is more space for the (air and fuel) mixture to enter the premix chamber and the combustion chamber**.** The optimum axial and radial temperatures of combustion without swirler are 930°C and 942°C, respectively which are less than temperatures of combustion with swirler. This is because there was no proper mixture of air and fuel and therefore, the combustion intensity was lower. Flame temperature increases as the swirl angle is increased from 20 degrees to 50 degrees but reduces at swirl angle 60 degrees. This is because the turbulence created by the blades from 20 to 50 degrees was convergent but divergent beyond 50 degrees suggesting that more turbulence was created between 20 to 50 degrees. This effect is likely to lead to increase in swirl number which invariably might cause significant reduction in CO, NO_x and CO_2 emissions. This assertion is corroborated by the work of [8].

Moreover, the interesting results from the profiles indicate that irrespective of the swirl angles, the wavelength and oscillation of the axial and radial temperature follows similar manner. This is more evident in the distribution of the optimum temperature (Figure 8).

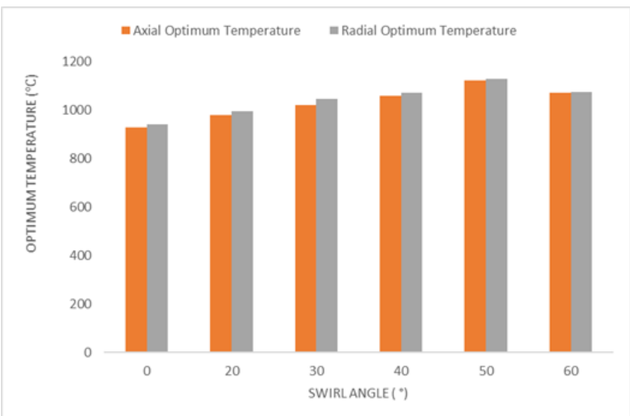


Figure 8. Effect of swirl angle on optimum temperature of straight blade swirler

It should be noted that 6 blades at 50 degrees yielded the best performance with the highest axial temperature of 1121°C and highest radial temperature of 1130°C indicating 21% improvement over the non-swirler blades. This is not surprising since agitation increases turbulent mixing. The result will suggest that high agitation is generated at 50 degrees, which led to high combustion characteristics.

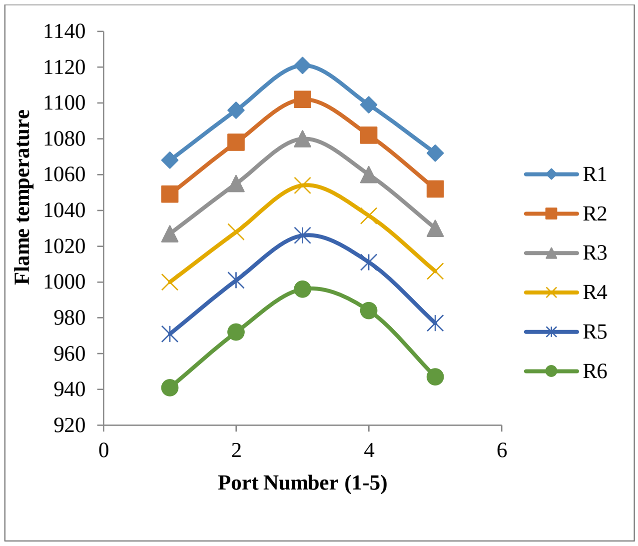


Figure 9. Flame temperature variation with port numbers (Swirler at 50°)

Table 1. Quadratic curve fit equations for flame temperature profile generated for R1 to R6

Radii	Quadratic Curve fit
R1	$y=-11.29x^2+68.39x+1009.40$ $R^2=0.94$
R2	$y=-11.57x^2+70.43x+988.60$ $R^2=0.96$
R3	$y=-11.50x^2+70.10x+966.60$ $R^2=0.95$
R4	$y=-11.50x^2+70.10x+938.20$ $R^2=0.96$
R5	$y=-12.00x^2+74.20x+906.60$ $R^2=0.97$
R6	$y=-12.29x^2+76.11x+874.80$ $R^2=0.98$

Note: x and y represent flame temperature and port number, respectively

Figure 9 shows variation of flame temperature downstream at different radius and port numbers for a swirl angle of 50°. It revealed that temperature increases as port number increases at critical port number 3. Beyond port 3, there is drastic decay in the flame temperature. The quadratic curve fit equations generated for R1 to R6 with R^2 of nearly 1.0 are highlighted in the Table 1. Based on the fact that optimal performance was obtained at swirl angle of 50° and port number 3 for all the radii investigated, the data in this regard was used to quantify flame temperature decay trend at different radius (Radially) as shown in Figure 10.

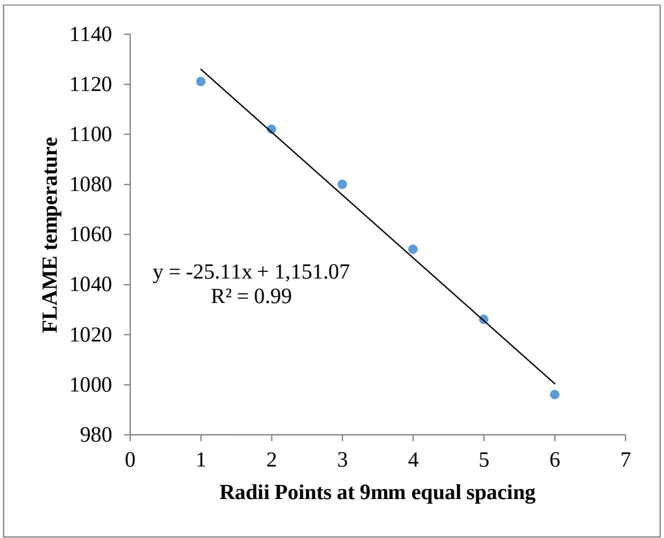


Figure 10. Flame temperature decay trend at different radius (Port 3 and swirl angle 50°)

4. CONCLUSIONS

The effect of swirl on the temperature characteristics in straight blade liquid fuel swirl burner has been examined through the measurements of radial and axial temperature distributions using chromium-zinc thermocouple with an effective range of 0 to 1300℃. Measurements were carried out for the straight blade swirl generator made up of 6 number of blades at angles 20°, 30°, 40°, 50° and 60° and fired by conventional diesel in a developed experimental model liquid fuel burner. In order to assess the performance of the swirler, measurements were also made for burner without swirl generator. It was found that swirl blades created turbulence in the combustion chamber of a swirl burner which enhanced the radial and axial flame temperature and combustion intensity. The results showed that the highest axial temperature of combustion with and without swirler was 1121℃ and 930℃, respectively and the highest radial temperature of combustion with and without was 1130℃ and 942℃, respectively. It was inferred that swirl has great potential to significantly affect the thermal profile of liquid fuel swirl burner. The effect was enhanced as the blade swirl angle was increased until a threshold was reached.

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