

EMISSION REDUCTION FROM BURNER SYSTEM BY VARYING SWIRLER BLADE ANGLE

MOHAMMAD NAZRI MOHD JAAFAR^{1*}, MUHAMAD SHUKRI ABDUL MOOKMIN² & ISMAIL SAMAT³

Abstract. This paper presents the effect of varying the blade angle of a small radial air swirler on reducing emissions such as oxides of nitrogen (NO_x) and carbon monoxide (CO). In this research a liquid fuel burner system with four different radial air swirler blade angles has been investigated using 163 mm inside diameter combustor of 280 mm length. Tests were conducted using kerosene as fuel. A radial flow air swirler with curved blades having 40 mm outlet diameter was inserted at the inlet plane of the combustor to produce swirling flow. Fuel was injected at the back plate of the swirler outlet using central fuel injector with two fuel nozzles pointing axially outwards. The swirler blade angles and equivalence ratios were varied. Tests were carried out using four different air swirlers having 30°, 40°, 50° and 60° blade angles, respectively. A NO_x reduction of more than 50 percent was achieved for blade angle of 60° compared to the 30° blade angle. CO emissions were also reduced by 72 percent for 60° blade angle compared 30° blade angle.

Keywords: Swirling flow; industrial burner; NO_x emissions; CO emissions; curved blade

Abstrak. Kertas kerja ini mempersembahkan pengaruh mengubah sudut bilah pemutar udara aliran jejarian yang kecil dalam mengurangkan emisi seperti oksida nitrogen (NO_x) dan karbon monoksida (CO). Dalam kajian ini, satu sistem pembakar berbahan api cecair menggunakan empat pemutar udara aliran jejarian yang berlainan sudut bilah diuji di dalam kebuk pembakar berdiameter 163 mm dan panjang 280 mm. Ujian dijalankan menggunakan kerosin sebagai bahan api. Pemutar udara aliran jejarian dengan bilah terlenkung berdiameter keluaran 40 mm dipasang pada satah masukan pembakar bagi menjana aliran berpusar. Bahan api dipancarkan pada plat belakang keluaran pemutar menggunakan pemancit bahan api pusat dengan dua nozel bahan api menghala keluar secara paksi. Sudut pemutar udara dan nisbah setara diubah-ubah. Ujian dilaksanakan menggunakan empat pemutar udara yang berlainan sudut, iaitu masing-masing 30°, 40°, 50° dan 60°. Pengurangan NO_x melebihi 50 peratus dicapai untuk sudut bilah 60° berbanding pada sudut bilah 30°. Emisi CO juga dikurangkan sebanyak 72 peratus pada sudut bilah 60° berbanding pada sudut bilah 30°.

Kata kunci: Aliran berpusar; pembakar industri; emisi NO_x ; emisi CO; bilah terlenkung

1.0 INTRODUCTION

The need to protect the environment from combustion generated NO_x has led to considerable demand to improve burner design. Previously, attention has been given

^{1,2&3} Department of Aeronautical & Engineering, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM, Johor, MALAYSIA

* Corresponding author: Email: nazri@fkm.utm.my

to gas turbine used in aero engines and for power generation in stationary plant. Intense research has been going on to develop gas turbine with very low NO_x emissions. In recent years considerable attention has been paid to reducing NO_x from process burners. However, in order to minimize NO_x emissions from gas turbine combustor it is necessary to increase the primary zone airflow and to improve air and fuel mixing. Many low-emission gas turbine combustor designs aim to pass as much air as possible through the combustor head and add the remaining air further downstream in a dilution zone with no air needed for film cooling [1]. The primary zone is a burner configuration [1]. Thus, many of the methods used to effectively minimize NO_x emissions from gas turbine can be adapted to burner configurations and conditions. This work is based on the low NO_x radial swirler work of Al-Kabie [2], Escott [3] and Kim [4] applied to burner applications of the 5-45 kW thermal input.

The effects of increased levels of NO_x in the atmosphere are wide reaching. In the atmosphere NO is rapidly oxidised to NO_2 and in this form plays an essential role in the formation of tropospheric ozone and photochemical smog, and is oxidised to form nitric acid that may then be deposited as acid rain [5]. At ground level, increased concentrations (above 0.06 ppm) of NO_2 can cause respiratory problem [6].

The legislation of NO_x emission limits in many parts of the world has substantially complicated the process of burner design. Attempts at lowering NO_x emissions by reducing the flame temperature will lead to reduced flame stability or increased CO emissions. The lowest NO_x emission obtainable in a given configuration is always limited by unacceptable stability problems or CO emissions. Thus the burner design has become a trial-and-error, multi-parameter optimisation process.

Basically there are two techniques of controlling NO_x : those which prevent the formation of nitric oxide (NO) [7, 8] and those which destroy NO from the products of combustion [9–11]. In the present work the former methods are employed.

The methods that prevent the formation of NO involved modifications to the conventional burner designs or operating conditions, such as lean primary zone, rich primary zone, rich/lean, or reduced residence time, since the main factors governing formation of NO is temperature and oxygen availability. However, the rich/lean method tends to increase carbon monoxide (CO) and unburned hydrocarbon (UHC). Advanced combustor designs are needed for reducing all four major pollutants simultaneously over a range of thermal or engine power outputs. This gives rise to the use of variable geometry combustor and staged combustion to cope with the demands of burner turndown and power variations in gas turbines, when the overall air-fuel ratio (A/F) is increased as power is reduced. For ultra low NO_x emissions, lean premixed-prevaporised combustors and catalytic combustors are being developed.

In the present work, the use of swirler to generate swirling flow is being adopted as a measure to prevent the formation of NO_x emissions.

2.0 SWIRLING FLOW

Swirling flow is a main flow produced by air swirled in gas turbine engine. Such flow is the combination of swirling and vortex breakdown. Swirling flow is widely used to stabilize the flame in combustion chamber. Its aerodynamic characteristics are obtained through the merging of the swirl movement and free vortex phenomenon that collide in jet and turbulent flow. This swirl turbulent system could be divided into three groups and they are jet swirl turbulent with low swirl, high jet swirl with internal recirculation and jet turbulence in circulation zone. Each and every case exists due to the difference in density between jet flowing into the combustion chamber and jet flowing out into the atmosphere from the combustion chamber.

When air is tangentially introduced into the combustion chamber, it is forced to change its path, which contributes to the formation of swirling flow. The balance in force could be demonstrated by the movement of static pressure in the combustion chamber and can be calculated by measuring the distribution of the tangential velocity. Low pressure in the core center of the swirling flow is still retrieving the jet flow in the combustion chamber and thus, produces the not-so-good slope of axial pressure. Meanwhile at the optimum swirl angle, the swirl finds its own direction and as a result, swirl vortex is formed.

The recirculation region in free swirl flow is shown in Figure 1. Due to assumption that the flow is axially symmetrical, thus only half of the flow characteristics are discussed. The recirculation region is in the OACB curve. The point B is known as stagnation point. The flow outside of the OACB curve is the main flow, which drives the recirculation along the AB solid curve. The ultimate shear stress could happen at points near to point A, along the boundary of recirculation. The condition of zero axial velocity is represented by dotted curved line AB. Every velocity component decreases in the direction of the tip. After the stagnation point, the reverse axial velocity will disappear far into tip, the peak of velocity profile will change towards the middle line as an effect of swirling decreases.

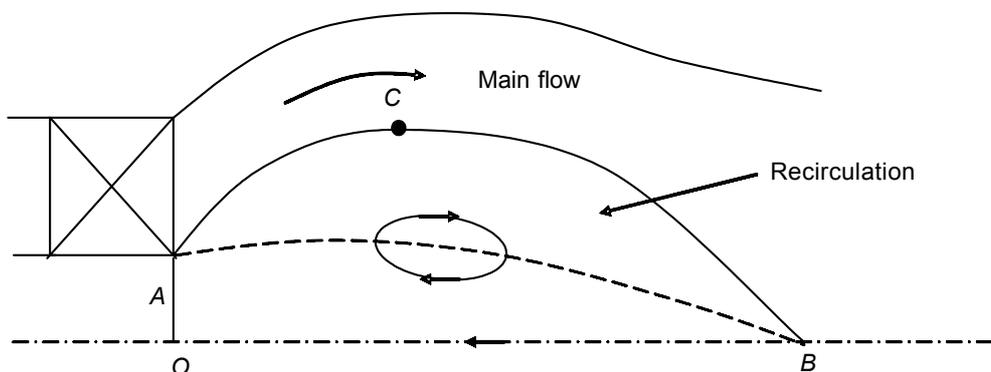


Figure 1 Recirculation zone in swirling flow

As the level of applied swirl increases, the velocity of the flow along the centerline decreases, until a level of swirl is reached at which the flow becomes stationary. As the swirl is increased further, a small bubble of internal recirculating fluid is formed. This, the vortex breakdown phenomenon, heralds the formation of large-scale recirculation zone that helps in stabilizing the flame. It has been suggested ([12] and [13]) that the large torroidal recirculation zone plays a major role in the flame stabilization process by acting as a store for heat and chemically active species and, since it constitutes a well-mixed region, it serves to transport heat and mass to the fresh combustible mixture of air and fuel.

The level of swirl or swirl strength can be represented in term of swirl number. Determining the swirl number is of great importance in burner design since it contributes to the correct setting for the swirl blades. Past researchers have studied the effect of varying the blade angle, which in turn vary the swirl number, on combustion performance. Drake and Hubbard [14] studied the effect of swirl on completeness of combustion and discovered that there was an optimum swirl blade setting. Claypole and Syred [15] investigated the effect of swirl strength on the formation of NO_x . They varied the swirl number from 0.63 to 3.04 using natural gas (mainly methane). At swirl number of 3.04, much of the NO_x in the exhaust gases was recirculated into the flame front. The total emissions of NO_x were reduced, however, at the expense of reduced combustion efficiency.

Mohd-Jaafar *et al.* [16] investigated the effect of using swirling flows on reducing NO_x . They varied the radial air swirler blade angles from 28.9° to 84.5° and tested using natural gas only and found out that 25% and 33% NO_x emissions reduction were achieved at burner pressure loss of 40 mm and 10 mm H_2O , respectively. These were achieved not at the expense of increased in unburned hydrocarbon (UHC) and carbon monoxide. Actually, when tested at burner pressure loss 10 mm H_2O , it was reported that these emissions were reduced rather than increased. They found that for burner pressure loss of 10 mm H_2O that the optimum blade angle was 51.1° and for the burner pressure loss of 40 mm H_2O tests the optimum blade angle was 74.3° .

Al-Kabie [2], on the other hand, demonstrated that there is no significant effect on NO_x emissions by varying the blade angle from 20° to 60° , hence varying the swirl number from 0.41 to 3.25, respectively. However, it was reported that at very high swirl number of 3.25, NO_x emissions were considerably higher than the rest at all associated equivalence ratio for two different inlet air temperature of 400 and 600 K. This may be due to the increased residence time in the rich stabilizing shear layer and hence increased NO_x emissions. The same effect was demonstrated when natural gas was used in replacement of propane.

Another way to increase the strength of swirl without changing the blade angle is to decrease the blade depth of the swirl. Kim [4] studied the effect of decreasing the blade depth of a small radial swirler with 40 mm outlet diameter having a blade angle of 45° . The effect of increasing the swirl number in this way was seen clearly, especially at 740 K, on decreasing the emissions of NO_x . Combustion efficiencies were also

improved as the swirl strength increased. Increasing the swirl strength also extend the lean flammability limits.

Another way to reduce emissions is by inserting an orifice plate at the exit plane of the swirler. Mohamad Shaiful and Mohd. Jaafar [17] found that by inserting the orifice plate of different sizes managed to reduce NO_x emissions by more than 15%.

Other earlier researchers who studied on the effect of varying the swirl strength were mainly interested on the flow pattern and temperature profiles resulted from varying the swirl strength. They were emphasizing the effect of swirl on the generation of toroidal central recirculation zones and flame geometry rather than the effect of swirl strength on emissions formation. Mestre [18] on the other hand, compared the effect of swirling and non-swirling system on combustion. It was demonstrated that the existence of swirl help improves combustion efficiency, decreases all pollutants and increases flame temperature. It was also reported that during the presence of swirl, a shorter blue flame was observed indicating good mixing while non-swirling system showed a longer yellow flame indicating that there is still some fuel left unvaporized.

In the present study, the effect of using four different swirler blade angles to vary the swirl strength was investigated. The air swirlers were changed by dismounting it from the combustor test rig and replacing it with different blade angle air swirler.

3.0 EXPERIMENTAL SET-UP

The general rig set-up for the liquid fuel burner tests is shown in Figure 2. The rig was placed horizontally on a movable trolley. The air is introduced through the inlet pipe and flows axially before entering the combustor through the radial swirler of 40 mm outlet diameter where the amount of air entering the combustor is controlled by the air swirler minimum area. The rig is equipped with a central fuel injector. The inside diameter of the combustor is 163 mm and the length is 280 mm. The combustor was cooled by the ambient air. The air entering the combustor was passed through a plenum chamber of the same diameter where the air swirler (Figure 3) was installed at its exit plane and the fuel was introduced in this chamber.

The exhaust sampling probe is mounted at the end pipe. The gas analyzer used in these tests was the portable MSI Dragger gas analyzer that measures oxides of nitrogen and carbon monoxide.

4.0 TEST CONDITIONS

Tests were carried out at around ambient temperature for inlet air since there was no preheating devices used in these tests. Air was supplied from the main air compressor in the laboratory.

The air supply pressure was metered using an air pressure regulator. This air supply was splitted into two, one to supply air to the combustion chamber and the other to

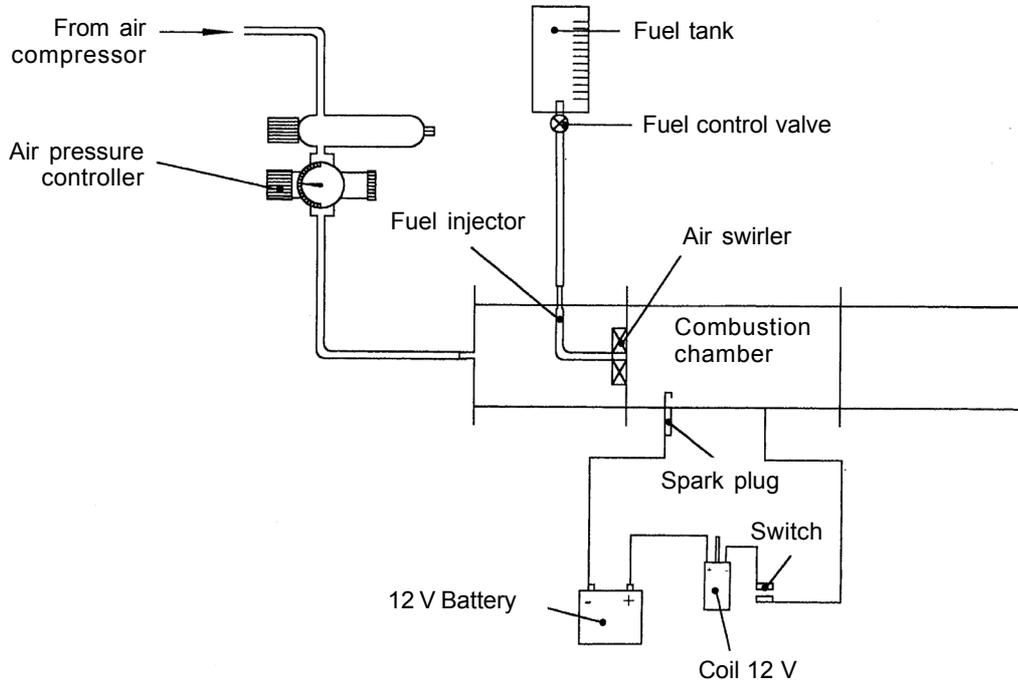


Figure 2 Set-up of experimental rig

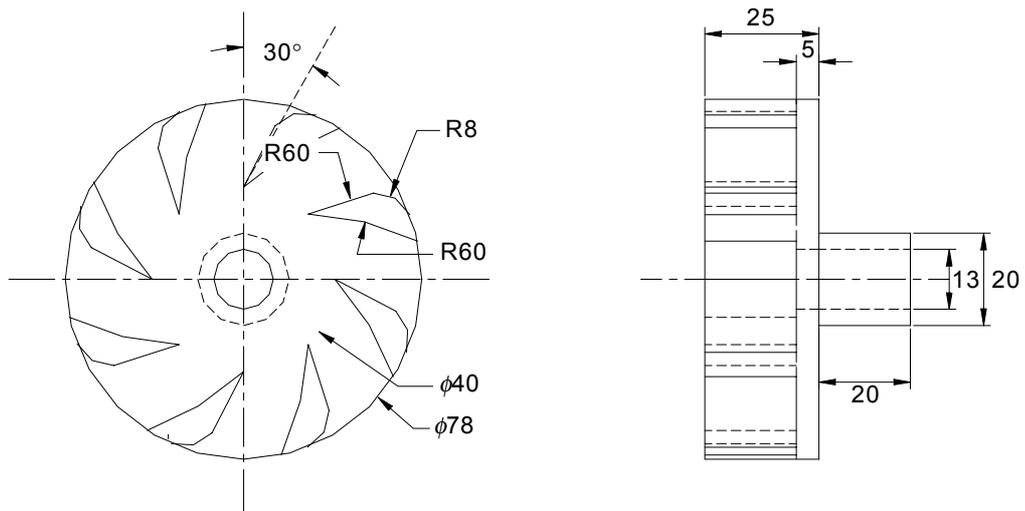


Figure 3 Schematic drawing of 30° air swirler (all dimensions in mm)

compress the fuel in the fuel atomiser, to help in atomising the fuel to smaller droplets.

Kerosene was used as fuel throughout the entire investigation. The parameter that was varied is different swirler vane angles and fuel flow rates to see the effect of lean and rich conditions on emissions formation. The variations in fuel flow rates are presented as equivalent ratio.

Equivalent ratio is defined as the ratio of actual fuel-air ratio to stoichiometric fuel-air ratio. Therefore, lower value of equivalent ratios means that the combustor is operating lean or at fuel-lean conditions, whereas higher value of equivalent ratios means the opposite.

Preliminary tests were conducted to investigate different fuel injectors to determine the best fuel injector to be used in these tests. Results showed that the radial two fuel nozzles was the one that provide good atomisation of the fuel.

5.0 EXPERIMENTAL RESULT AND DISSCUSIONS

Figures 4 and 5 show the effect of increasing the blade angle on exhaust emissions from burner system. Tests on exhaust emission were carried out using four swirler blade angles of 30°, 40°, 50°, and 60°.

5.1 Effect of Swirling Flow on NO_x Emissions Formation

Figure 4 shows vast reduction in oxides of nitrogen (NO_x) emissions when the blade angle was increased from 30° to 60°. This was apparent for the whole range of operating

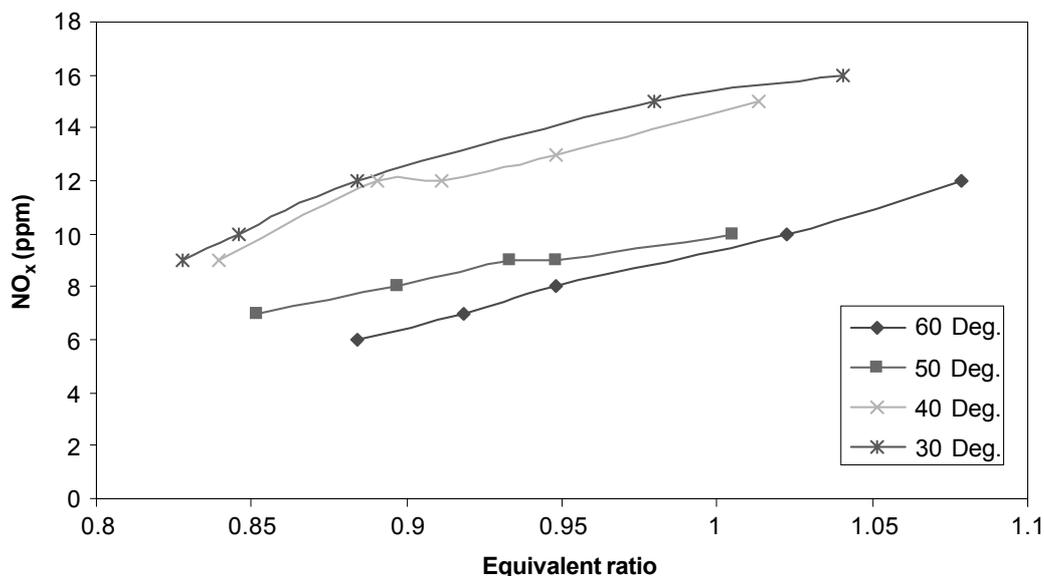


Figure 4 Effect of NO_x emissions on equivalent ratio at different vane angles

fuel flow rates. Emissions level of below 16 ppm was obtained for all range of operating equivalent ratios from 0.82 to 1.08. This, in general indicates that this burner system that incorporates the usage of swirling flow is able to retard the formation of NO_x emissions. This is in agreement with the other researchers such as Kim [4] and Al-Kabie [2].

From Figure 4, it can be seen that NO_x reduction of near 50% was achieved for blade angle of 60° compared to 30° at the same equivalent ratio. This proved that swirl does help in mixing the fuel and air prior to ignition and hence reduces NO_x emissions.

5.2 Effect of Swirling Flow on CO Emissions Formation

Figure 5 shows carbon monoxide emissions plotted against equivalent ratio for all air swirlers. There was more than 38% decrease in carbon monoxide (CO) emission when increasing the vane angle from 30° to 50° at equivalent ratio of 0.95. The reduction increases when increasing the vane angle from 30° to 60° . A CO emissions reduction of greater than 72% was achieved at the same equivalent ratio which indicate that swirling flow does help in mixing the fuel and air thoroughly prior to ignition. This is evident throughout the whole operating equivalent ratios from 0.82 through to 1.08 and also for all four swirlers.

The content of carbon monoxide emission decreases with the increase in equivalent ratio, i.e. increasing in fuel flow rate, meanwhile the NO_x emission rise with the increase in fuel flow rate. This was anticipated due to the fact that any measure of decreasing

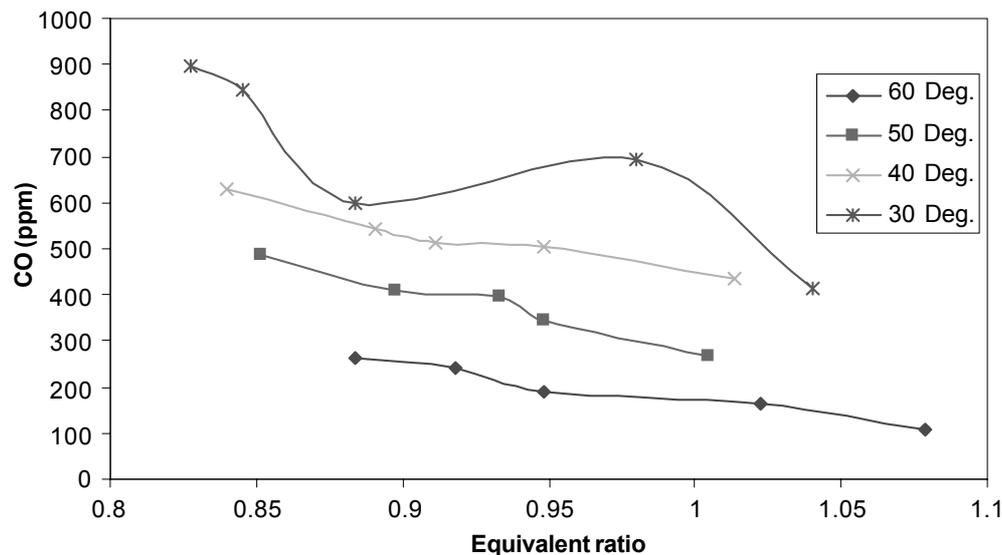


Figure 5 Effect of CO emissions on equivalent ratio at different vane angles

NO_x will tend to increase CO since both emissions were on the different side of the balance.

6.0 CONCLUSION

An NO_x emissions reduction of about 50% was obtained at equivalent ratio of 0.95 when using higher blade angle air swirler compared to that of the lower blade angle air swirler at the same equivalent ratio. CO emissions were also reduced greatly, that is a 72% reduction was obtained when using higher blade angle air swirler compared to that of the lower blade angle air swirler. NO_x emissions of less than 16 ppm was achievable over the whole range of operating equivalent ratios when using higher blade angle air swirler at the same fuel flow rate.

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