Proceedings of the 4th WSEAS Int. Conf. on HEAT TRANSFER, THERMAL ENGINEERING and ENVIRONMENT, Elounda, Greece, August 21-23, 2006 (pp115-121)

FLAME COOLING AND RESIDENCE TIME EFFECT ON NO_x AND CO EMISSION IN A GAS TURBINE COMBUSTOR

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Abstract
Combustion with Swirl is used extensively in gas turbine combustors to achieve stable combustion at minimum emissions, and good temperature distributions over a wide range of operation. In this paper the effects of flame cooling and residence time on NO_x and CO emission in a can type gas turbine combustor have been investigated experimentally. The flame cooling and residence time are obtained by introducing the secondary air tangentially through four slots at the upstream of the combustor around the flame (secondary air swirl). The flame temperature and residence time are varied by changing the cross section area of the slots (increase the swirl intensity). Measurement of the emission concentrations and the temperature distributions have been undertaken for diesel fuel at an overall air /fuel ratio of (78:1). A significant effect of swirl intensity of the secondary air on both radial and axial temperature distributions has been recorded. Results of this study indicate that the flame cooling and residence time have great effect on emission characteristics in the gas turbine combustor under investigation.

Key-Words :- Flame cooling, Residence time, Emission, Gas turbine, Combustor, NO_x

1. Introduction

The gas turbine is in many respects the simplest type of power apparatus available. It is completely self-contained requiring no boiler or external heat source as it burns fuel and converts the heat released into mechanical power within a single assembly. Therefore, investigation of combustion process in a gas turbine combustor is of a prime importance. There are many studies [2 to 10] concerning the combustion phenomenon and emission characteristics in a gas turbine combustor with particular interest in the combustion processes. However, the resent interest progress of gas turbine application and of environmental considerations require more studies towards achieving higher power outputs at minimum emission, and satisfy wider range of operating requirements.

Flame stability at minimum emission is the basic requirements of gas turbine combustors. The primary air flow pattern is of a prime importance to flame stability. Different types of air flow patterns employed but one feature common to all is creation of a toroidal flow reversal that entrains and recirculates a portion of the hot combustion products to mix with the incoming air and fuel. These vortices are continually refreshed by air flowing through holes. One of the most effective ways of inducing recirculation in primary zone is to fit swirler in dome around the injector. This type of recirculation provides better mixing than that normally obtained by other means such as bluff bodies, because of the characteristics of swirling flows such as high turbulence, strong shear region, and rapid mixing rates [1].

Effects of primary air swirl and swirl strength on emission and temperature characteristics have been reported by several investigators [2 and 3]. Results indicate that the swirl strength improves mixing process and effects emission formation, combustion intensity, and temperature distributions. It is revealed that the increase of swirl strength causes a decrease of carbon-monoxide rapidly at the primary zone, and the nitric oxides concentrations is lower with primary air swirl than without swirl. On the other hand reduction of swirl causes reduction of combustion intensity within the initial port of the flame and close to the center line. The temperature in up stream portion of the combustor is lower for strong primary air swirl rather than weak one.

Effect of swirl direction (i.e. co-or counter rotating swirl) and wall geometry on emission for the fuel nozzle/rich burn at cruise condition at an equivalence ratio of 1.9, the nozzle- combustor interface geometry was varied from a flat wall to a sloped wall of 45 degrees have been investigation by Micklow, and Shivarman, [4]. It is shown that the co-rotating swirl direction with sloped wall has a substantial effect on reducing emission.

Effect of swirl angle, injection position relative to the swirler flow distribution within the combustor and air/fuel ratios on combustion have been studied by Kitajima et al., [5]. The emission results obtained by optimization of these parameters were NO_x less than 10 ppm and, CO less than 15 ppm (at 15% O_2).

An altra-low NO_x gas turbine combustor has been described and tested for cogeneration systems by Sato and Mori, [6]. The combustor called a double swirler staged combustor, utilizes three staged premixed combustion for low NO_x emission. The unique feature of the combustor is its tertiary premix nozzle located downstream of double swirler premixed nozzle around the combustor. Results showed that NO_x level is maintained at less than 3 ppm (at 15% O_2) over the range of output between 50% and 100%. Emission of CO and UHC are maintained at 0 to 1 ppm (at 15% O_2)

The effect of radial distribution of swirl on the thermal behavior of two different pre-mixed flame using a double concentric premixed swirl burner (co- and counter) has been examined by Gupta, Lewis, and Daurar [7]. The results suggest significant effect of co- and counter swirl distribution in flame and the NO_x emission levels.

A low NO_x emission combustor with multi-hole pre-mixer pre-vaporizer has been designed and investigated by Lin, Peng, and Liu, [8]. The experimental results demonstrated large NO_x emission reduction of the multi-hole pre-mixer pre-vaporizer compared with the base line design that the pre-mixer and pre-vaporizer tube without multi-hole. The configurations of multi-hole pre-mixer per-vaporizer had great influence on NO_x emission reduction.

A low NO_x combustor with lean burn characteristic for 20 kW has been developed and studied by Yoon, and Lee, [9]. The study is performed at high temperature and high pressure up to 5 bar with an air inlet temperature 560K. They found that NO_x increased while CO decreased as increasing air inlet temperature and pressure. NO_x decreased, but CO increased as increasing mass flow rate of air. Also as a result of this study, NO_x can be reduced up to less than 42 ppm at 15% of O_2 at design condition.

Therefore the intermediate zone has to be studied, designed, and investigated more intensively in order to create a perfect mixing of the secondary air with the flue gases to achieve complete combustion with low emission, and good temperature distributions. For this reason, the aim of this work is to investigate the effect of flame cooling and residence time on NO_x and CO emission characteristics in a can type gas turbine combustor by tangential entry of the secondary air through four slots at up stream of the combustor around the flame.

2. Experimental Test Rig and Instrumentation

A schematic diagram of the experimental test rig is illustrated in Fig. 1 consists of a can type gas turbine combustor, primary and secondary air supply systems, fuel supply system, and measuring instruments. Details of the combustor used are shown in Fig. 2. The combustor is provided with an air blast atomizer, air swirl systems, and ignition system. The primary and secondary air supplied to the combustor by means of three air blowers, through a net pipe line connected with control valves, orifice meters to control and measure flow rates of the air. Fuel system consists of a fuel tank, connecting pipes with regulating control valves and air blast atomizer to supply fuel spray cone at constant pressure. A high pressure air is supplied to the atomizer through an individual pipe with control valves and pressure gauge.

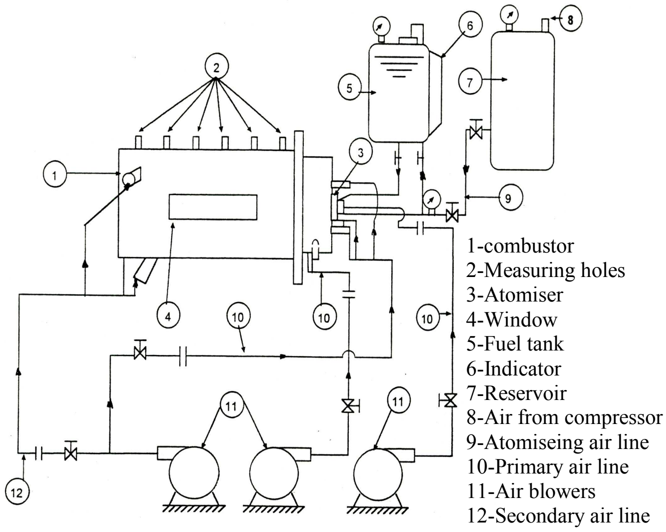


Fig. (1) Schematic diagram of experimental test rig.

The temperatures and emission concentrations inside the combustor are measured by means of the ENERIC combustion analyzer (Model 2000). The analyzer measures two temperatures, five different gases (CO, NO_x, SO_2, O_2, UHC) draft, and smoke. It is also provided with a software and SHARP printer (Model 1600) to compute the carbon dioxide concentration, excess air, and combustion efficiency.

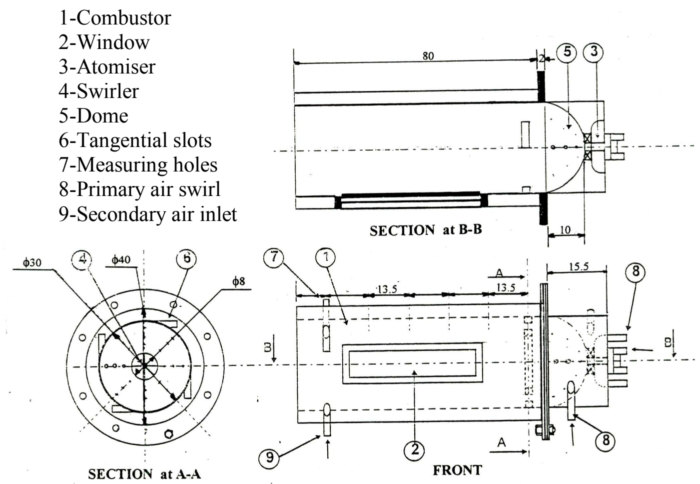


Fig.(2) Details of the combustor

A number of experiments are carried out in order to study and investigate the effect of flame cooling and residence time on emission characteristics in a can type gas turbine combustor. The experiments are curried out for an overall air/fuel ratio of (78:1). The flame cooling and residence time are obtained by introducing the secondary air tangentially through four slots at the upstream of the combustor around the flame (secondary air swirl). The flame temperature and residence time are varied by changing the cross section area of the slots (increase swirl intensity). In case (A) the total slots area is 4000 mm^2, case (B) is 5000 mm^2 and case (C) is 6000 mm^2. The measurements are taken through six measuring holes, six readings for each hole at different radial positions (from wall to center line of the combustor). After the measurements of each hole are taken, the sampling probe is cooled to the room temperature, and the reading of oxygen concentration is about 21% before it is inserted into the next hole.

3. Results and Discussion

This paper Primary concerned the effect of flame cooling and residence time on emission formation (NO_x and CO) in a can type gas turbine combustor. The experiments have been undertaken at the following operating conditions. Air/fuel ratio of (78:1), and total slots area of (6000, 5000, and 4000 mm^2). The results obtained for temperature, NO_x, and CO emissions are set out in Figs.(3 to 9). Also results for CO_2 concentrations are presented in Fig. (10).

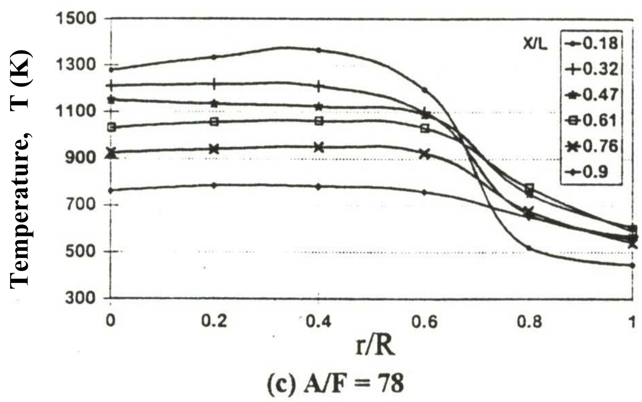
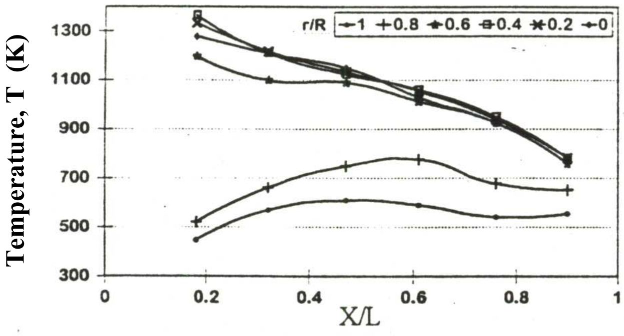


Fig. (3) Radial distribution of temperature at different axial distances, slots area 6000 mm^2



(c) A/F = 78

Fig. (4) Axial distribution of temperature at different axial distances slots area 6000 mm^2

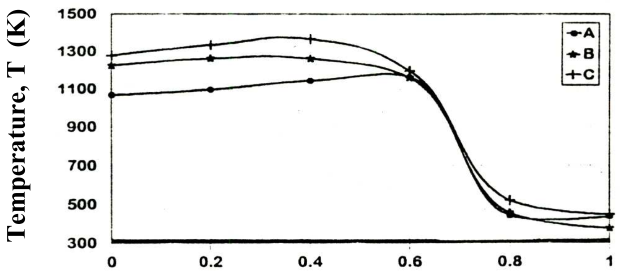
Figures 3 and 4 show the radial and axial temperature distributions along the combustor with slots area of the secondary air entrance of 6000 mm^2, case (C). It may be noted that this slots area gives the lowest swirl intensity among the three cases of slots area used. However, these data will be used later in this paper as a reference when the effect of secondary air swirl intensity is discussed. It may be remarked in Figs. 3 and 4 that the swirl obtained at this slot area causes a significant decrease in the radial and axial temperature distributions (from r/R=0.6 to 1.0) at X/L ratios of 0.18, and from upstream to the combustor exit. It may be noted in Fig, 3 that the maximum and minimum temperatures have been recorded at X/L = 0.18. One may refer the maximum temperature at this point to the high fuel/air ratio existing in the region around this point. Also this could be considered as an effect of recirculation. But at the center region of the flame, the temperature is about 90% of the flame temperature value as suggested in [10]. The minimum temperature obtained is expected at this point which is very close to the entrance of the secondary air at upstream.

In Fig. 4 two different trends of axial temperature distributions at different radial distances are noticed. The first trend is obtained for the radial distances from r/R = 0.0 to 0.6 (inside the flame region) while the second trend is for the radial distances from r/R= 0.8 to 1.0 (near the combustor wall). In the first trend, the temperature starts with maximum values at upstream of the flame region and decreases gradually to post flame and the combustor exit; but in the second trend, the axial temperature increases as x/L increase from 0.18 to 0.61 and then decrease in to the direction of the combustor exit. However, these two different trends are expected and may be attributed to the effect of the secondary air for the first trend and the heat transfer caused by the flame region on the surroundings for the second trend.

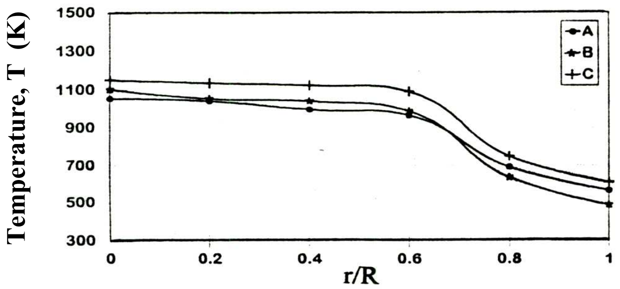
Figure 5 shows the effect of changing the slots area of the secondary air entrance (increase swirl intensity) on the axial and radial temperature distributions at different X/L. It may be noted that, the higher temperature is obtained with case (C) of slots area of the secondary air entrance. The increase of the secondary air swirl intensity by decreasing the slots area of the secondary air causes a reduction in the temperatures especially at the flame region Fig. 5a, this is because the increase in secondary air swirl improves the mixing between the fuel, combustion products and air. At outlet of the combustor there is insignificant influence of swirl intensity on the temperature Fig. 5f.

Nitric oxide (NO_x) concentrations obtained at case (C) of slots area of 6000 mm^2 in the radial and axial directions are shown in Figs. 6 and 7. The results show that the radial concentrations of NO_x take the same trends of the temperature, and the formation of NO_x depends on the temperature. The maximum concentrations of nitric oxides are obtained at the flame region, (at r/R = 0.0 to 0.6), then decrease to a very low concentration in the direction to the wall of the combustor. This is may be attributed to the effect of the secondary air which is introduced to the combustor at upstream. Also the results show that the concentrations of NO_x in the axial direction increase with increase of the axial distances from X/L = 0.32 and reach a maximum at X/L = 0.47, then decreases in the direction to the outlet.

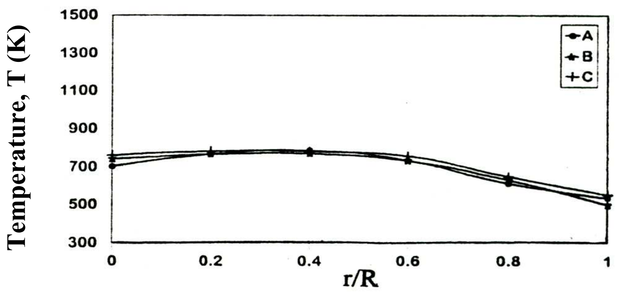
Results of carbon-monoxide (CO) concentrations in the radial and axial distances along the combustor, with total slots area of 6000 mm^2 are obtained. The maximum concentrations of CO are remarked in the flame region at upstream of the combustor (over 2000 ppm), and the minimum values are near the wall of the combustor because of the entrance of secondary air which surrounds the flame, also the results indicate that the concentrations of CO decreases in the direction to the out let, and it is zero at outlet of the combustor.



(a) X/L = 0.18

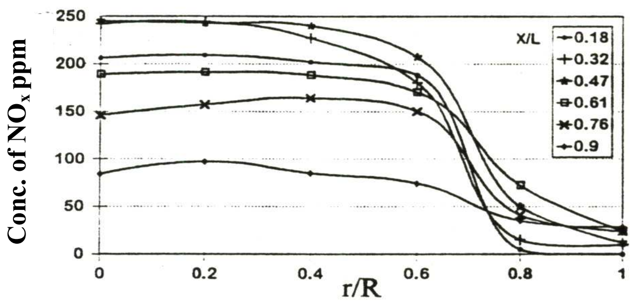


(c) X/L = 0.47



(f) X/L = 0.9

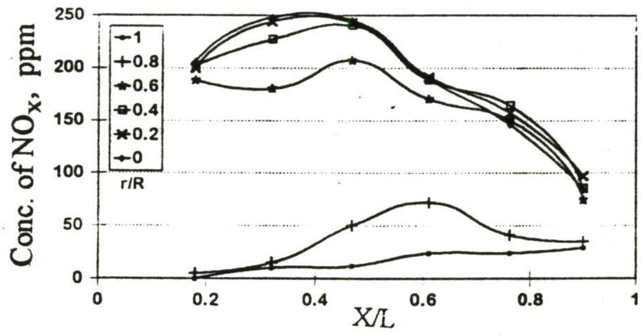
Fig.(5) Effect of changing slots area of secondary air entrance on temperature distributions at different axial distances.



(c) A/F = 78

Fig. (6) Radial concentration of NO_x at different axial distances slots area 6000 mm^2

The concentrations of carbon-dioxide (CO_2) are calculated by the "ENERAC" as a function of the oxygen concentrations and the type of fuel used. It may be noted that, at normal operation with the type of liquid fuel used, and complete combustion,



(c) A/F = 78

Fig. (7) Axial concentration of NO_x at different Radial distances slots area 6000 mm^2

the concentrations of CO_2 in the combustion gases are between 5 to 6% of the combustion products at outlet of the combustor where the combustion is assumed to be complete. Fig. 10 shows the average concentrations and the effect of changing the slots area of the secondary air entrance on CO_2 at outlet of the combustor. It may be noted that the concentrations of CO_2 are increase with the decrease of the slots area which means complete combustion of CO.

The fuel used is containing sulfur, so that a sulfur-dioxide is present in the measurements, and it is about 60 ppm at outlet.

4 Conclusions and Recommendations

As a result of this experimental study the following conclusions are obtained.

1- Secondary air swirl has greatly improved the temperature distributions inside the combustor used in this study. Minimum temperature of 450 K is obtained at the wall of the combustor and maximum temperature at exit of 750 K, this is suitable for the material of the turbine. Also the flame is affected by swirl intensity of secondary air, the increase of swirl intensity causes a considerable reduction in temperature of the flame and increase the residence time.

2- An average reduction of 65% in NO_x emission at outlet has been obtained by changing the total slots area from 6000 to 4000 mm^2. The concentration of CO is zero at the outlet of the combustor.

For further studies a number of items have been recommended:

1- Curry out an experimental work and theoretical studies to investigate the influence of secondary air swirl on the flow field in gas turbine combustor considering thermal energy equations as well as species conservation equations.
2- Study the effect of changing slots number and angle of the secondary air entrance on the combustion and emission characteristics in gas turbine combustor.

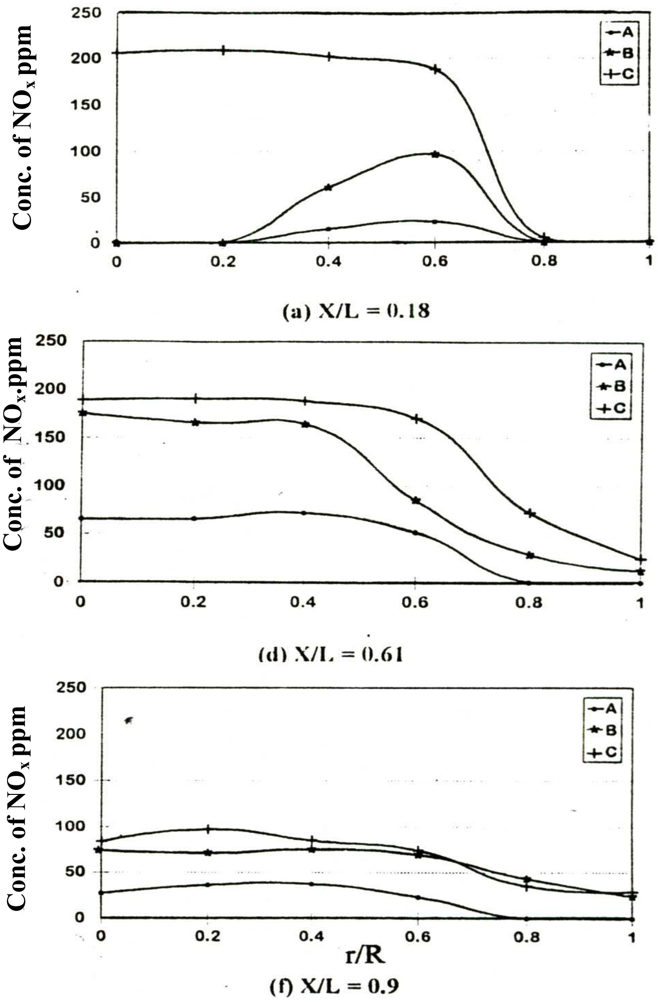


Fig.(8) Effect of changing slots area of secondary air entrance on NO_x distributions at different axial distances.

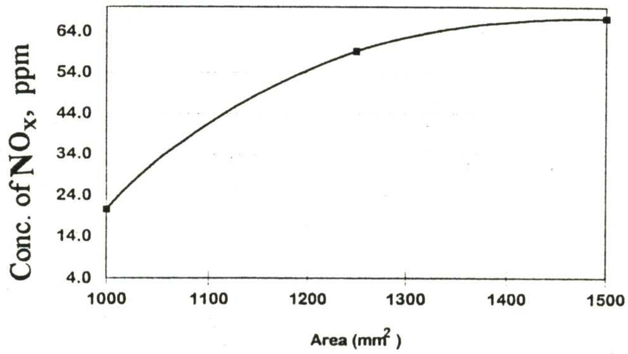


Fig. (9) Variation of average NO_x at outlet with different slots areas

Fig. (10) Variation of average CO^2 at outlet with different slots areas

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