INFLUENCE OF FUEL INJECTION TECHNIQUES ON COMBUSTION PERFORMANCE OF MULTI-JET SHEAR LAYER COMBUSTION

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Abstract

Experimental work was carried out to study the effect of fuel injection techniques on the high intensity non-swirl multi-jet shear layer combustion performance of a four-hole conical burner. Two modes of gas oil fuel injection were investigated using a simple type atomiser with four holes positioned 45^o to the horizontal axis and can be manually aligned either offset or inline with the hole centre. This enables the fuel to be radially injected either straight into or between the jet shear layers. The test results show that the fuel injection techniques had strong influence on the fuel atomisation and the fuel/air mixing and hence the combustion performance. The NOx results of the offset fuel injection showed a typical NOx profile of an aerodynamic lean/rich combustion. The inline fuel injection produced better combustion performance as compared to the offset injection but was limited by a narrower stability. However, the relatively high combustion inefficiency , as indicated by high CO and UHC emissions, with the inline injection mode even though at high pressure losses indicate the problems of inadequate atomisation and mixing which were attributed mainly to the aerodynamic features of the system concerned.

Keywords

Fuel Injection, Atomisation, Rapid Fuel-Air Mixing, Non-swirling Flow, Combustion Performance.

Introduction

The attainment of perfect mixture homogeneity prior to combustion is of paramount importance to the success of lean low-emissions combustors. Ideally, the burner geometry should have mixing characteristics capable of generating combustion aerodynamics in which the system can be operated not only with high-turn-down ratios but also with low levels of harmful emissions. The rate of pollutant formation, especially NOx, is very closely related to the degree of fuel and air mixing. At the present time, lean premixed combustion appears to be the only technology available for achieving ultra-low NOx in practical gas turbine combustors [Lefebvre, 1995]. However, its potential application in a high-turn-down ratio burner is limited by the narrow flame stability limit [Andrews et al., 1988] and in high-temperature and high-pressure systems the problems of spontaneous ignition and flashback in the mixture preparation zone are always encountered [Plee and Mellor, 1978]. Alternatively, non-premixed or rapid fuel air mixing techniques of fuel preparation have become increasingly popular due to the capability of operating the combustion in the fully mixed mode at a wider flame stability limit range and with no problems associated with mixture preparation. In non-premixed techniques the fuel is directly introduced into the air stream at the burner entry port so that they are molecularly mixed in the high turbulence mixing region. The mixing processes are strongly dominated by turbulent mixing phenomena. The level of turbulence generated is strongly dependent on the magnitude of pressure loss across the burner. Abdul Aziz, et al. [1987] compared the influence of pressure loss on the combustion performance of gaseous and liquid fuels and found that liquid fuels were more sensitive to pressure loss term. This was because the pressure loss governs the atomisation jet velocity which determines the fuel drop size. An increase in the pressure loss produces more high turbulence generating region and an injection of liquid fuels in this region not only decreases the fuel droplet size but also increases the fuel and air turbulent mixing rates.

The objective of the present experimental work is to further investigate the combined merit of simultaneous fuel atomisation and fuel-air mixing technique of mixture preparation in an interacting non-swirling shear layer burner. The position of the fuel injection relative to the air jets is important as this influences the access of the fuel to the turbulent shear layer and hence may influence mixing rates. The present work used of one of the non-swirl flame stabilisers, i.e. grid cone, as shown in Figure 1, that has been tested in Leeds at mostly lean primary zones gas turbine situations.

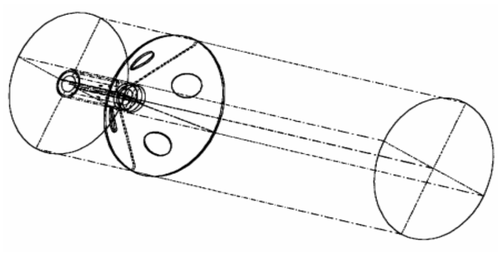

Figure 1 - A schematic diagram of the grid cone system

A simple 2D-flow visualisation investigation by Al-Shaikhly [1989] using dyed water and a 3D-computational isothermal study by Mustafa [1999] showed that this type of non-swirl flow system produces an internally generated aerodynamics of rich/lean combustion, as schematically illustrated in Figure 2.

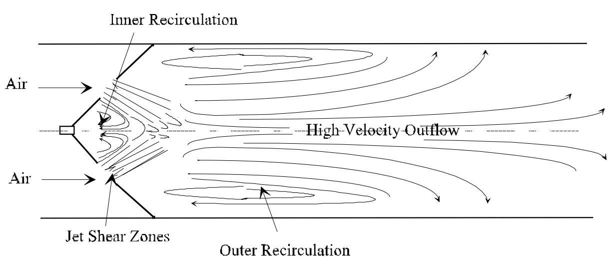

Figure 2 – Aerodynamic flow patterns of the grid cone system.

Two modes of direct liquid fuel injection into the combustor were employed. The fuel was injected either directly into or in between the high turbulence jet shear layer mixing region. The same fuel injection configuration has been investigated by Andrews et al. [1984] using the jet mix stabiliser. The test results at primary zone gas turbine conditions showed that this type of non-swirl stabilised flames technique achieved low NOx emissions with a good stability margin compared with the premixed systems.

Experimental Set-Up

A schematic diagram of the test facility is shown in Figure 3. The test rig is primarily consisted of a 12.7 mm diameter four hole grid cone burner with a simple central liquid fuel injector, a 76 mm diameter 330 mm long uncooled cylindrical combustor, pressure and temperature measuring devices, an electrical heater , an ignitor and also gas sampling probes. The uncooled combustion chamber is a typical burner configuration of a flame stabiliser with a downstream tube burner.

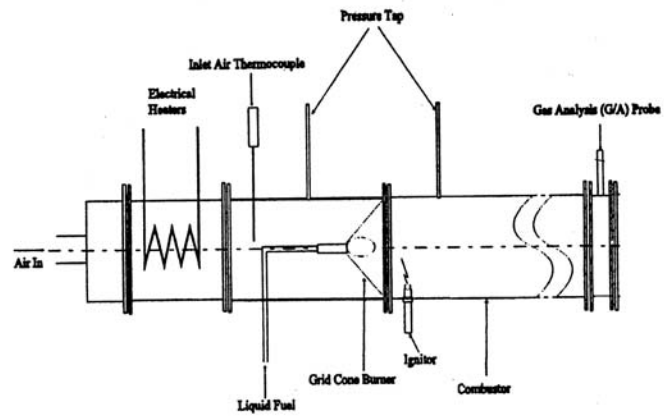

Figure 3 - Experimental test rig

The central liquid (gas oil) fuel injector is of a simple air-assisted type atomiser with four holes (0.5 mm diameter) positioned 45^{o} to the horizontal axis and can be manually aligned either offset or inline with the hole centre. This enables the fuel to be radially injected either straight into or between the jet shear layers. In order to investigate the merit of these injection modes, the liquid fuel (gas oil) was supplied only by gravity. The central fuel injector together with injection configurations are shown in Figure 4. The inline configuration is aimed at promoting simultaneous atomisation and rapid fuel and mixing by direct injection of the fuel into each high velocity jet. With the offset configuration, the fuel is injected between jet shear layer thus creating locally richer zones than the inline design and subsequently better stability can be created.

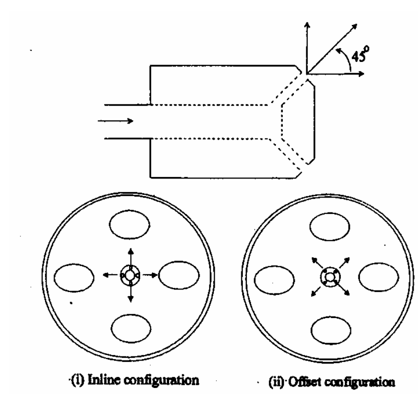

Figure 4 - Fuel injection system

Results and Discussion

Weak extinction

The weak extinction limit was determined by decreasing the fuel flowrate until either of two events: (1) sudden drop in the flue gas temperature measured just downstream the first combustor (2) UHC and CO emissions showed a dramatic rise. The weak extinction results in Table 1 show that the offset injection mode had a better stability than that of the inline mode. As there was no direct air assisted fuel atomisation for the offset injection mode, the combustible mixture was prepared by means of simultaneous vaporisation and mixing during the vaporisation period. This produced the mixture of locally high fuel rich zones which was responsible for a better flame stability. However, the inline injection mode also had an excellent flame stability due to the internally generated rich/lean aerodynamics combustion system. The direct injection of the fuel into the highly turbulent mixing shear layers produced simultaneous atomisation and mixing. Furthermore, additional fuel atomisation and fuel-air mixing processes may have also took place on the central axis downstream of the cone exit where the jet shear layers impinged.

Table (1) Weak Extinction Results

Burner	Present Design	
Hole Diameter (mm)	12.7	
Blockage (%)	89.0	
Mach No.	0.012	
Inlet Temp. (K)	295	
Pressure Loss, ΔP (%)	2	2
Injection Mode	Inline	Offset
Weak Extinction (ϕ)	0.22	0.17

NOx emissions

Figure 5 shows the effect of fuel injection mode on the formation rate of NOx emissions for different burner pressure drops. The lower NOx emissions of the inline injection mode as compared to that of the offset injection mode were mainly due to locally more fine fuel drop sizes and more uniform mixture distribution which reduced the hot spot NOx producing zones. This demonstrates the importance of fuel preparation technique on the NOx formation characteristics . The NOx results of the offset fuel injection show a typical NOx profile of an aerodynamic rich/lean operation combustion system. At a burner pressure loss of 2%, the maximum NOx emissions was at an equivalence ratio of around 0.55 indicating that the local rich zone was near stoichiometric with maximum NOx production. The combined effects of local rich zones and insufficient oxygen as the rich/lean combustion approached the stoichiometric operation caused the NOx emissions to decrease and become lower than that of the inline fuel injection at equivalence ratios richer than 0.85. However, the NOx results for a burner pressure loss of 3% and 4% shows no clear evidence of rich/lean combustion. This could indicate that the fuel and air mixing with the offset injection mode had been improved by the higher pressure loss operation.

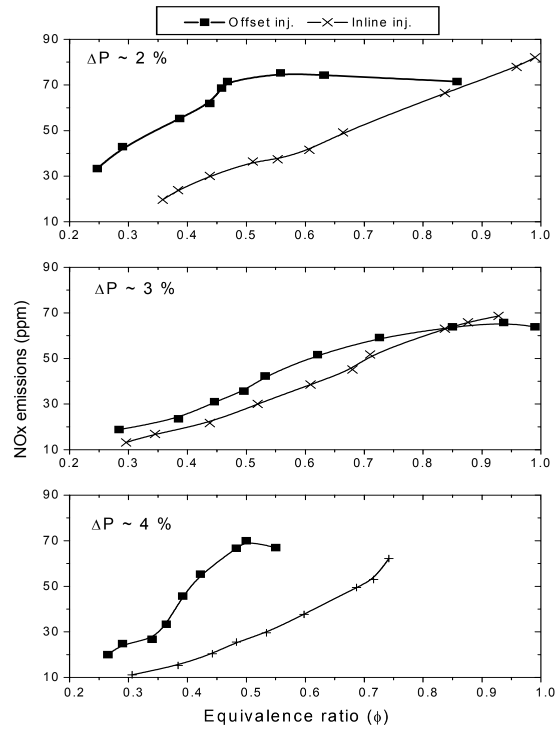

Figure 5 - NOx emissions as a function of equivalence ratio

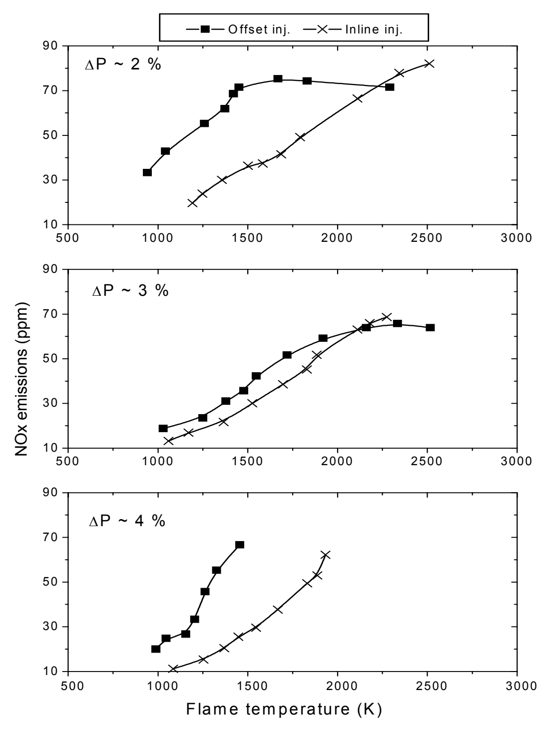

Figure 6 - NOx emissions as a function of flame temperature

The NOx emissions as a function of flame temperature in Figure 6 again demonstrates a similar NOx trend to Figure 5. At the same flame temperature, the offset fuel injection produced higher NOx emissions than for the inline fuel injection except near stoichiometric conditions. This was mainly due to the poor atomisation and mixing characteristics of the offset fuel injection produced high local near stoichiometric air fuel ratios and hence NOx producing zones. As the combustion approached the stoichiometric operation the NOx formation rate steadily decreased owing to the locally insufficient oxygen availability in the fuel rich environment in spite of the high mean flame temperature. With inline fuel injection, the lower NOx emissions except near stoichiometric flame temperature were because the uniformity of fuel and air mixing was closer to the premixed system as compared with the offset injection mode.

UHC and CO emissions

The variation of UHC and CO emissions with equivalence ratio are shown in Figures 7 and 8, respectively. The offset fuel injection curves of the 2% and 3% pressure loss tests show a slow increase in the UHC and CO emissions until an equivalence ratio of around 0.45 – 0.55 beyond which a drastic increase took place. This was probably the mean equivalence ratio where the flame shifted further downstream of the burner. The increased UHC and CO emissions are considered to be due to the local mixtures were richer than the stoichiometric values. Additionally, as the flame axially shifted further downstream there was insufficient post flame residence time for the UHC and CO burnt-out. Near stoichiometric combustion, the high UHC levels were due to the UHC from the local rich zone bypassing the flame zone and the high CO levels were because of the high equilibrium CO formed in the local rich zone. Unfortunately, for the 4% pressure loss operation, further tests up to stoichiometric condition could not be carried out due to very intense, noisy and unstable operation due to combustion-induced pressure oscillations.

The UHC and CO emissions of the inline fuel injection were lower than that of the offset mode except at equivalence ratios leaner than approximately 0.40 - 0.55. The increased fuel momentum with equivalence ratio as a result of the high fuel mass rate penetrated more into the highly turbulent mixing shear layers caused better fuel atomisation, vaporisation and hence mixing with the air. The improved quality of the fuel drop sizes together with the better fuel and air mixing resulted in more efficient combustion than for the offset fuel injection and hence lower UHC and CO emissions. The higher UHC and CO emissions of the inline fuel injection at equivalence ratios less than 0.40 - 0.55 were mainly due to the poorer lean stability. However, an associated reduction in the NOx emissions, as shown in Figure 5, indicates local stoichiometric burning around single droplets did not occur.

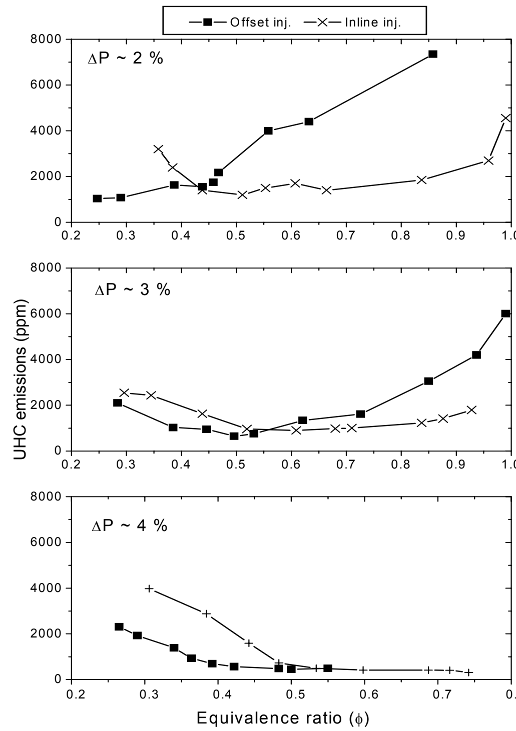

Figure 7 – UHC emissions as a function of equivalence ratio

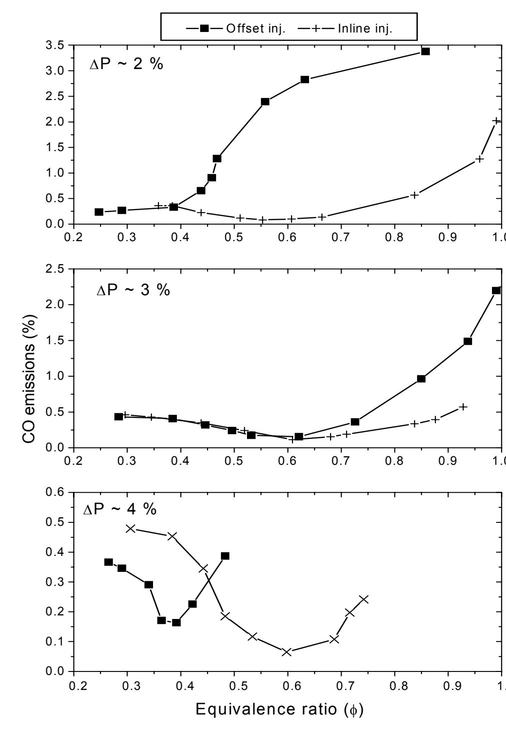

Figure 8 – CO emissions as a function of equivalence ratio

Combustion ineffiency

The combustion performance is expressed as combustion inefficiency taking into account the presence of unburnt hydrocarbon and CO emissions in the exhaust gases. The combustion inefficiency curves as a function of equivalence ratio in Figure 9 clearly show the inline injection mode produced more efficient combustion with increasing burner pressure loss due to better fuel atomisation and improved fuel and air mixing as it approached stoichiometric operation. However, the still high combustion inefficiency suggest that even though the fuel was directly injected into the high turbulence region of shear layer there were still problems of fuel atomisation and fuel and air mixing. The poorer efficiency of the inline injection mode at leaner equivalence ratios (i.e. < ~ 0.4 –0.5) was attributed to higher emissions of CO and UHC as it approached a lean stability limit.

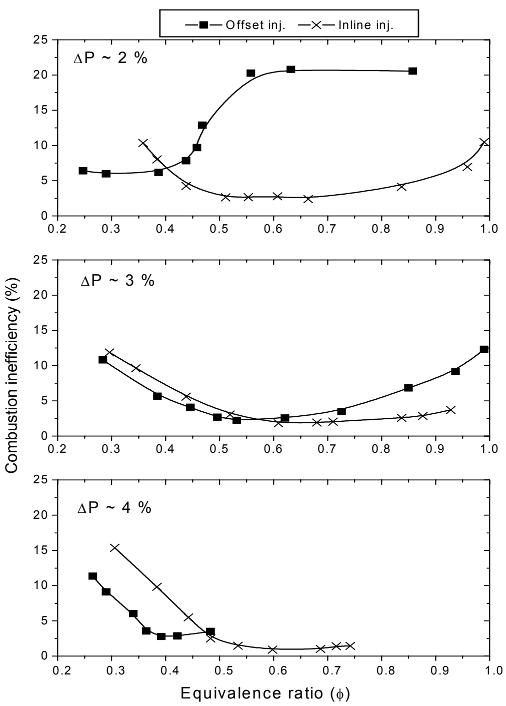

Figure 9 – Combustion ineffcicency as a function of equivalence ratio

Conclusions

1. The inline mode of fuel injection had narrower flame stability limit than the offset mode.
2. The NOx emissions of the inline fuel injection were lower than that of the offset mode except near stoichiometric conditions and thus exhibiting a typical NOx trend of a relatively well-mixed system.
3. The NOx profiles of the offset fuel injection showed a typical NOx trend of an aerodynamic lean/rich combustion system. The NOx, UHC and CO emissions of the offset fuel injection decreased as the pressure loss was increased.
4. The still high levels of UHC and CO with the inline fuel injection even though at high pressure loss indicate that the inline fuel injection of the grid cone burner has problems of poor atomisation and inadequate mixing.
5. The lower NOx emissions of the inline fuel injection at lean equivalence ratios were mainly associated with the factors resulting in the poorer lean stability. However, the associated reduction in NOx emissions indicates no local stoichiometric burning around single droplets occurred.

Acknowledgements

The authors would like to thank Universiti Teknologi Malaysia (financial support) and Univesity of Leeds (test facilities) to carry out this work.

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