TURBULENT MIXING PROCESSES IN A SWIRLING-MULTIPLE JET CONFINED CROSSFLOW CONFIGURATION

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ABSTRACT

The aim of the present work is to provide global insight on the turbulent mixing processes typically occurring in a rectangular perspex mixing module simulating a sector of an annular RQL gas turbine combustor, through an experimental investigation of non reacting multiple jet mixing with a confined swirling crossflow. The RQL (Rich burn - quick Quench - Lean burn) staged combustion concept has been proposed as one of the candidate technologies towards reducing NO_x emissions in gas turbine combustion systems. Mean and fluctuating momentum and scalar field distributions, mixing rate and standard deviation were determined in a number of different test cases obtained by parametric variation of flow and geometric configuration conditions. The results clearly indicate the sensitivity of the attained mixing quality on the particular flow arrangement, the momentum flux ratio and the effect of swirl induced in the primary zone.

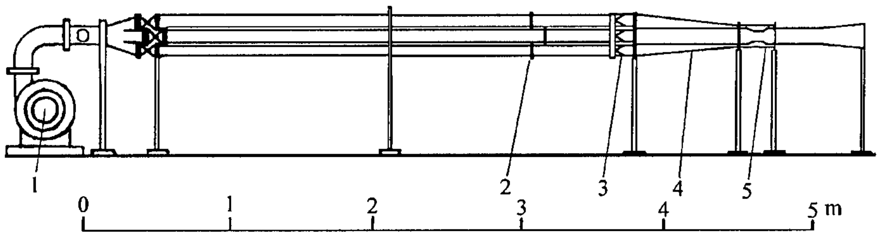
1. INTRODUCTION

The demand for air transportation and therefore its contribution to atmospheric pollution increases with time. Current and future gas turbine design has to meet the often conflicting goals of increasing engine efficiency, while diminishing the rates of NOx, CO and UHC per unit of fuel burnt. These requirements can be fulfilled either by the introduction of staged combustors (RQL) and/or lean premixed prevaporised (LPP) technology, (Peters [1]).

The RQL design approach is based on the idea of temperature control throughout the combustion chamber due to the strong temperature dependence of thermal NOx formation (Zeldovich mechanism). The combustion process thus takes place into two zones. Rich burning occurs in the primary zone of the combustor at equivalence ratios above 1.3, thereby reducing NOx formation by lowering the combustion temperature. Additional air enters the combustor in the form of injected jets in an intermediate quick-mix section. Of paramount importance for a successful RQL combustion process is the performance of the quick-quench step. Emphasis in this region is given on understanding the jet/crossflow interaction process (e.g. Novick and Troth [2]; Rosfjord et al [3]), or dilution hole aerodynamics, (Witting et al [4]; Holdeman et al [5], Srinivasan et al [6]), since these topics play a key role on the overall engine emission.

The second zone burns under lean conditions, where the remainder of the fuel is oxidised and the consuption of CO, UHC and soot, formed previously, is completed. The promising trends of RQL technology related to pollutant reduction has led to increasing emphasis on RQL research.

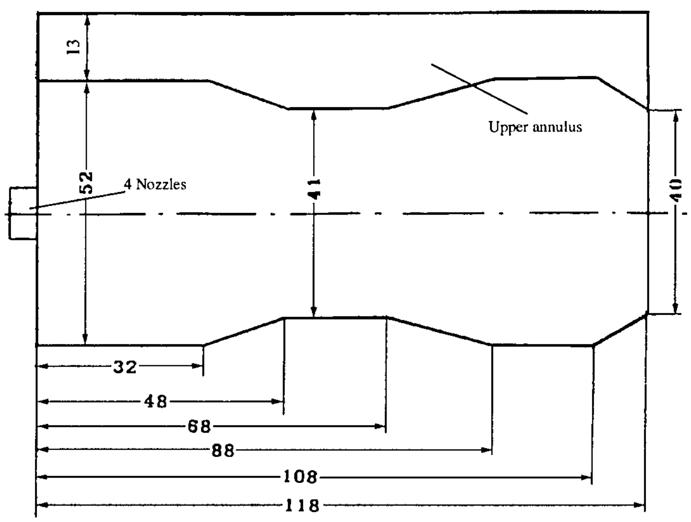
The optimisation of RQL design demands a detailed understanding of the internal flow structure in this type of combustors. The predominant flow variables which affect mixing quality appreciably are the jet to crossflow momentum flux ratios, the injector zone geometry and the type of swirling motion produced by the fuel nozzles in the primary zone. However, due to the experimental difficulties inherent in real combustion devices, recourse is often made to the study of 'equivalent' isothermal flow systems (e.g. Heitor [7]; Doerr and Hennecke [8]; Kalogirou and Papailiou [9]). Even though a direct analogy between the combusting and non-reacting experiments is clearly not possible, the experience gained by the latter is definitely valuable and can be tranfered to the hot flow case (Heitor and Whitelaw [10]). Within the discussed context, the aim of the present work is to provide global information on the turbulent mixing processes controlling the overall performance of a multiple-jet array/confined crossflow configuration under the above specified parametric variations.



1. Compressor 2. Orifice meter 3. Transition section 4. Inlet diffuser 5. Mixing section

SIDE VIEW

Figure 1. Schematic diagram of the experimental facility



MIXING MODULE

Figure 2 Geometry of the RQL mixing module

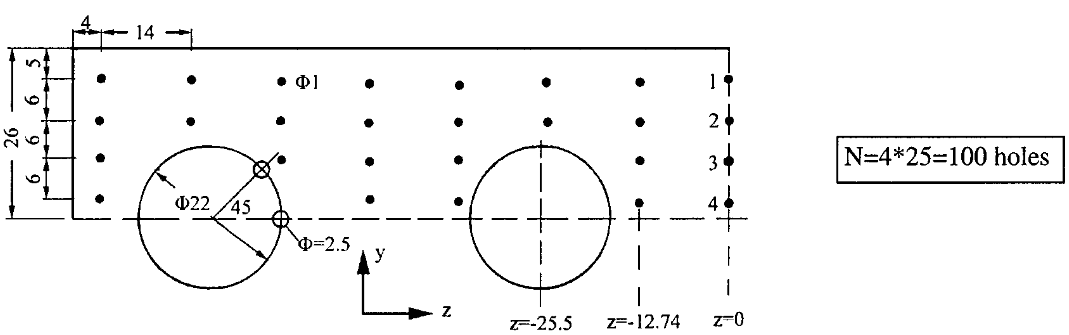


Figure 3 Combustor head geometry

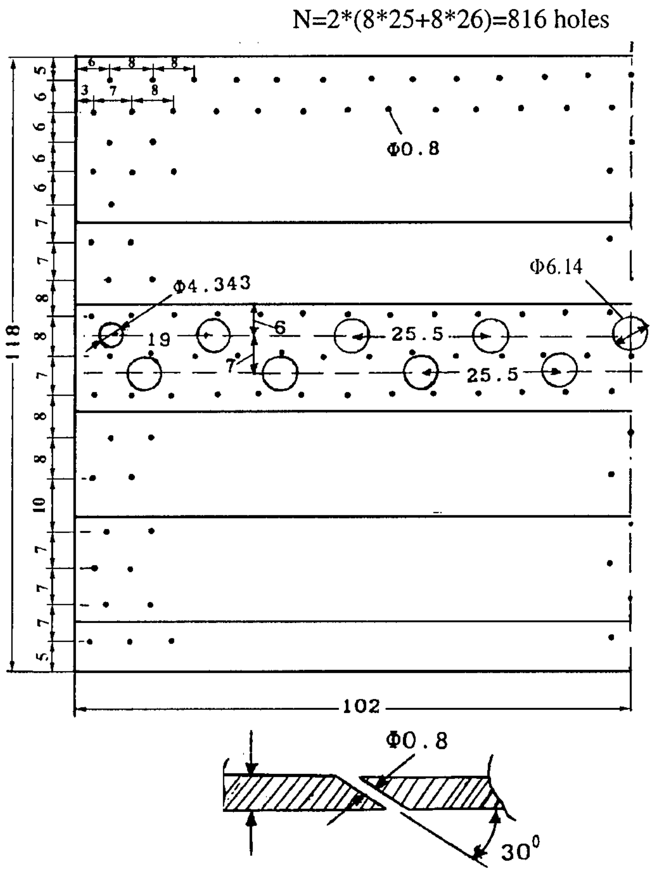


Figure 4 Liner cooling and jet injection area design

2. EXPERIMENTAL METHODS

2.1. Experimental facility

Figure 1 presents schematically the experimental set up where the isothermal mixing experiments will be performed. This apparatus, is an open circuit three-channel wind tunnel driven by two centrifugal compressors with maximum flow rate 0.16 kg/s at 0.5 bar overpressure. By means of a valve system, the supply airflow is divided into the jetstream, (annulus flow), and the mainstream. The mainstream is slightly heated relative to the annulus flow in the case that temperature field measurements take place. Three independently controlled cylindrical supplies feed the two annuli and the primary stream and the corresponding flow rates are metered by three orifice meters with precision better than 2%. The upper and lower jetstream and the main flow subsequently pass through settling chambers, honeycombs, round to orthogonal adapters and finally enter the rectangular mixing section.

The plexiglass model configuration to be studied is shown in figure 2. This rectangular module simulates a sector of an annular RQL combustor. The cold flow characteristics mainly affected the proportion of the total flow which is shared between the mainstream and the two annuli and the liner cooling hole geometry and distribution. Specifically, the primary and the jet stream flow rates are differently distributed in the constant density experiment in order to attain identical momentum ratios with the combusting case where the concentration of the streams differs significantly. The annulus flow was divided into three parts, (rich liner cooling, lean liner cooling and jet injection flow). The same also applies to the mainstream subdivision, into atomiser and combustor head cooling airflow.

On the combustor head, which is cooled by impingement cooling, four airblast atomisers (nozzles) are mounted, as shown in figure 3. The combustor head cooling air enters the primary zone through 32 holes which are located around the airblast atomisers where it is also used for combustion in the reacting flow case. The overall geometry of the impingement holes is also shown in figure 3. Each liner is cooled by effusion cooling, the design of which is shown in figure 4. The liner cooling holes have a 30° inclination. The jet injection region consists of two rows of holes in staggered arrangement and its design data are also presented in figure 4.

Temperature field measurements were performed with the use of a Hot Wire Anemometer (HWA) operating in the constant-current mode while, velocity measurements were carried out using two single-component forward scatter LDV systems.

2.2. The flow configuration examined

A number of flow configurations has been investigated using two sets of nozzles providing different flow conditions. The experimental cases tested are listed on the table 1 and are identical for both series of nozzles. Two different procedures were followed in order to reach the three momentum ratios of interest, i.e. J=80, 100 and 120. Each particular J was achieved either by maintaining the mainstream flow rate constant and varying the annulus flow, and vice versa.

Table 1. Flow conditions

A. $\dot{m}_P$ = const.							
test case	J	$\dot{m}$ (kg/s)	$\dot{m}_P$ (kg/s)	$\dot{m}_a$ (kg/s)	U_{j1R} (m/s)	U_{n-d} (m/s)	U_a (m/s)
#1	80	0.0867	0.0393	0.0474	48.88	5.46	8.68
#2	100	0.0936	0.0393	0.0543	55.997	5.60	9.95
#3	120	0.1000	0.0393	0.0607	62.597	5.72	11.12
B. $\dot{m}_a$ = const.							
#4	80	0.1110	0.0503	0.0607	62.597	6.99	11.12
#5	100	0.1046	0.0439	0.0607	62.597	6.26	11.12
#6	120	0.1000	0.0393	0.0607	62.597	5.72	11.12

Notes:

$\dot{m}$: total air mass flow
$\dot{m}_p$: mainstream mass flow
$\dot{m}_a$: annulus mass flow
U_{j1R}: the jet velocity at the first row of holes
U_{n-d}: the axial mainstream velocity at the necked - down region entrance.
U_a: annulus air velocity
J: momentum flux ratio which is defined by

$$J = \frac{\rho_a \cdot U_{j1R}^2}{\rho_p \cdot U_{n-d}^2}$$

2.3. The measurement matrix

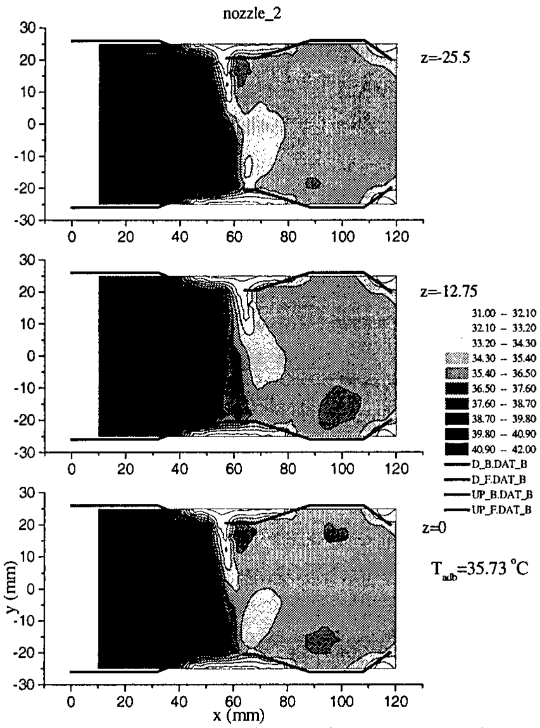
Figure 4 shows the various positions of measurement throughout the combustor module. In all configurations studied, measurements were performed along three different longitudinal planes namely, the vertical plane of symmetry (z=0) and two parallel nearby planes located at distances -12.75 mm and -25.5 mm apart from the central plane. The last plane passes through the center of the injector as shown in fig. Note that at some downstream distances, namely at x=10, 38, 78 and 95 mm, vertical transverses of temperature are obtained at more than three z-locations which are normally obtained at the remaining streamwise measuring stations.

3. RESULTS AND DISCUSSION

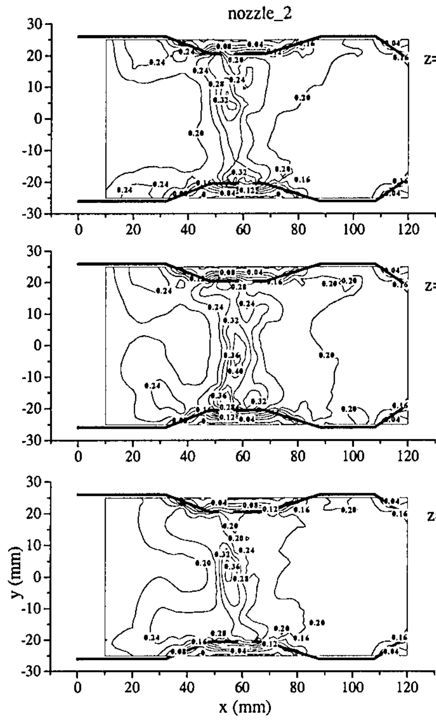
Using the two sets of nozzles mentioned above, (nozzle_1 and nozzle_2), detailed temperature measurements were carried out throughout the combustor perspex model for all the experimental cases listed in table 1. These measurements were performed first, because the scalar field distributions are direct indicators of the attained overall performance. This can conventionally be done by defining an adiabatic temperature which is the ideal mixing temperature for each experimental case (Kalogirou and Papailiou [11]).

At first, it was noticed that the set of nozzles_1 had an unsatisfactory effect on the resulting mixing quality. Therefore only the experimental results acquired with nozzle_2 will be presented here.

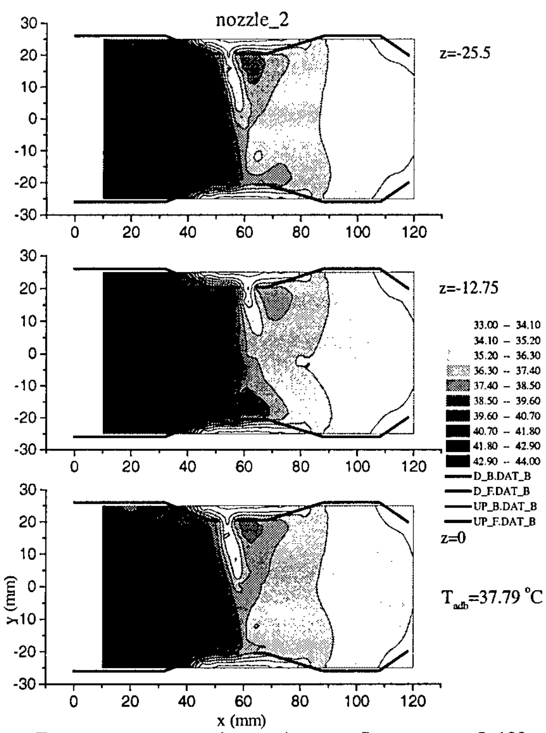
Figure 5 shows mean and fluctuating temperature distribution maps for two momentum ratios, namely j=120 and 100. The flow patterns associated with the higher momentum ratio are very close to an "ideal mixing" situation. This conclusion is based on the fact that in almost all the lean zone of the combustor prevails the ideal adiabatic temperature. It also should be noted that the injected jets and the resulting recirculations at their upstream part significantly affect the temperature distributions towards lower levels within the primary zone. In the lower momentum ratio ideal mixing is observed only in a small region downstream of the injected jets were adiabatic temperature is occurred. Regarding the turbulent temperature field, no substantial differences between these two flow cases can be noted. This leads to the conclusion that it is the momentum field that determines and drives the mixing processes in this injected jets/crossflow configuration.



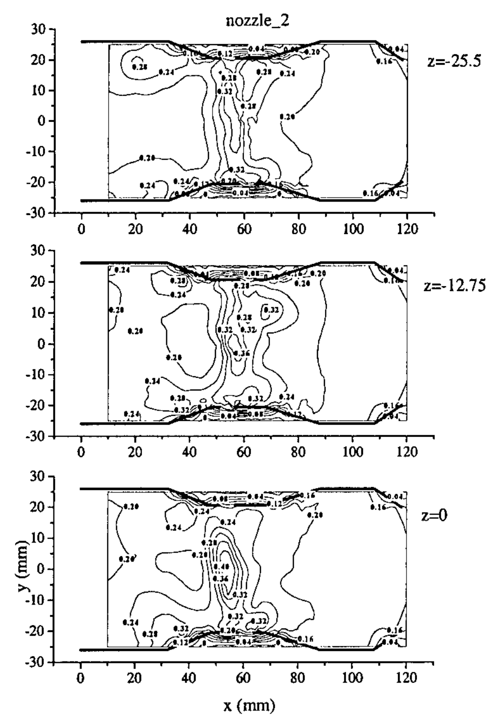
Temperature contour plot; mainstream flow constant, J=120



RMS temperature contour plots; mainstream flow constant, j=120

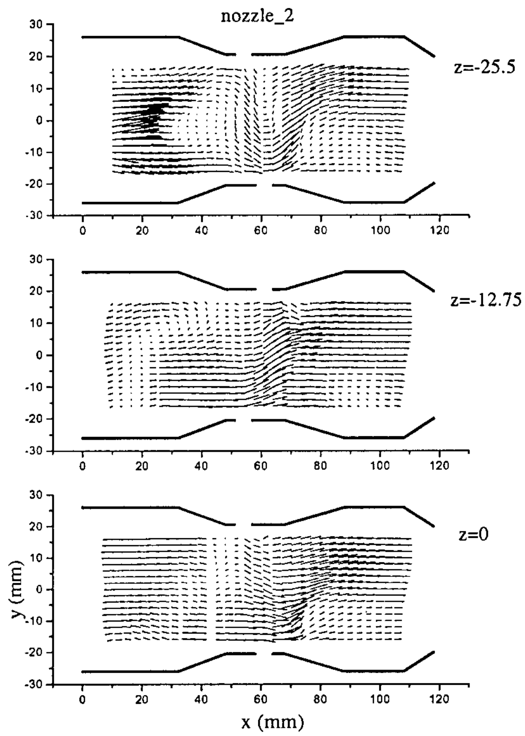


Temperature contour plots; mainstream flow constant, J=100

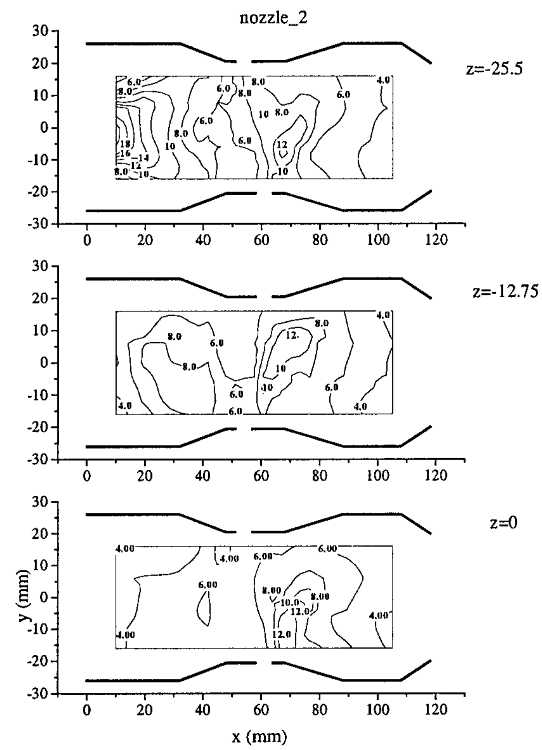


RMS temperature contour plots; mainstream flow constant, J=100

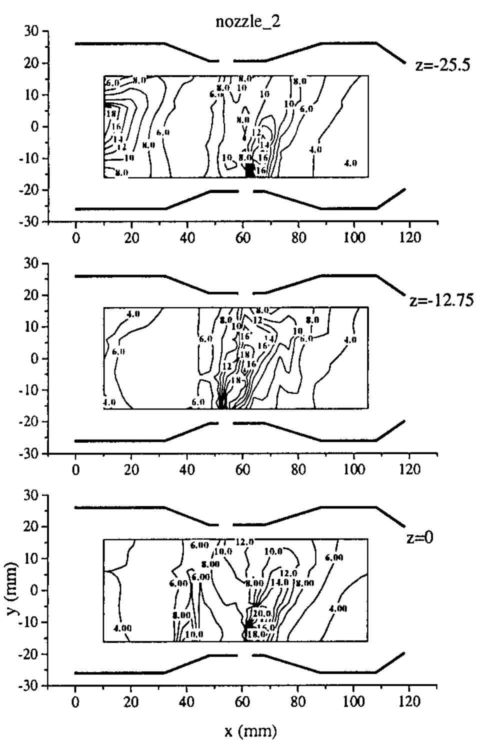
Figure 5 Mean and fluctuating temperature distribution maps for J=120 and J=100



Velocity vector plots; mainstream flow constant, j=120



Contour plots of Urms (m/sec);mainstream flow, J=120



Contour plots of Vrms (m/sec); mainstream flow constant, j=120

Figure 6 Mean and statistical velocity field maps for J=120

Mean and statistical velocity field maps for the two components u, and v, are presented in figure 6 for j=120. Extended recirculating motion can be seen on both sites of the jet incoming flow as a result of the interaction with the mainstream. The upstream recirculation results to significantly lower the temperature in the rich zone which is beneficial to NOx reduction. Towards the exit, on the other hand, a tendency for a "homogenisation" of the vector field is established, which is also reflected as an homogenisation of the resulting temperature field. This is also the case for the momentum field fluctuations as well.

Based on the above discussion, it is concluded that for j=120, the internal flow structure includes those flow characteristics that demonstrate excellent mixing performance and promising trends for pollutant reduction.

Acknowledgements

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Back