**The Effect of Jet Mixing on the Combustion Efficiency of a Hot, Fuel-
Rich Cross-Flow**

by

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**A thesis submitted in conformity with the requirements
for the degree of Masters of Applied Science
Graduate Department of Mechanical and Industrial Engineering
University of Toronto**

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Abstract

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Many combustion systems inject air into a hot fuel-rich cross-flow to minimize carbon monoxide and unburned hydrocarbon emissions. Examples include staged air injection in fluidized bed combustors, gas turbine engines, and electric arc furnace exhaust afterburners. Low CO and unburnt hydrocarbon emissions are important design objectives. Efforts in modeling combustion have failed in accurately predicting the levels of these emissions. The main aim of this study is to improve our understanding of the relationship between mixing, chemical kinetics, and combustion efficiency for air jets in a hot reacting cross-flow.

Carbon monoxide and hydrogen concentration measurements have been made for six different round jet configurations issuing air into a hot reacting cross-flow. The study of the performance of four different 9 round jets modules having different jet diameters indicated that the overall equivalence ratio has a significant effect on the maximum combustion efficiency. An equivalence ratio of approximately 0.8 leads to the best combustion efficiency for all of the 9 round jet modules. This result is similar to what is observed in premixed combustion. The predominance of the effect of the equivalence ratio suggests that some premixing between the jets and the cross-flow takes place prior

to combustion. The rest of the experiments were run such that the optimum mixing (according to cold flow theory) occurs at $\Phi=0.8$. The experiments also showed that, although the equivalence ratio does not control the location of the optimum point, it does affect the level of emissions. In fact, at constant equivalence ratio, low momentum flux ratios yield higher emissions. The number of jets affects the level of emissions. Larger number of jets provided better combustion efficiency. The unmixedness was measured for the 18 round jets module. This measurement showed the momentum flux ratio is a driving factor affecting mixing. The comparison of the combustion efficiency of H_2 and CO suggest that the reaction rate affect the level of combustion efficiency without affecting the location of the optimum.

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Nomenclature

<i>Symbol</i>	<i>Definition</i>
ϕ	Equivalence ratio
ϕ_M	Equivalence ratio in the primary reactor
UHC	Unburnt hydrocarbons
EAF	Electric Arc Furnaces
NO_x	Nitric oxides
J	Momentum flux ratio of the jets and the cross-flow
ρ_J	Density of the jets air
ρ_M	Density of the cross-flow gas
V_J	Velocity of the jets air
U_M	Velocity of the cross-flow gas
x	Axial position of the cross-section measured from the plane of the injection of the jets
H	Duct height
A_J	Total area of the cross-section of the jets
A_M	Area of the cross-section of the cross-flow
m_J	Total mass flow rate of the jets
m_M	Mass flow rate of the cross-flow
d	Diameter of the jets
D	Diameter of the cylindrical cross-flow

s	Spacing between jets
J_{OPT}	Optimum momentum flux according to Eq. (2-8)
C	Holdeman constant in the correlation given by Eq. (2-2)
RQL	Rich burn, quick mix, lean burn combustor
R	Radius of the cylindrical cross-flow
$R_{1/2}$	Mid area radius
n	Number of jets
m_F	Mass flow rate of fuel
m_A	Total mass flow rate of air
$[CO]_D$	Diluted molar fraction of CO
$[CO]_I$	Initial molar fraction of CO
$[H_2]_D$	Diluted molar fraction of H_2
$[H_2]_I$	Initial molar fraction of H_2
σ	Standard deviation of the total carbon concentration at $x/D=1.5$
μ	The mean value of the total carbon concentration at $x/D=1.5$
Σ	Unmixedness based on total carbon concentration

1. Introduction

1.1 Motivation

The increasing public awareness of the long-term global effect of combustion generated pollutants on the environment has increased the pressure on the industry to reduce pollutants emissions. Amongst the most targeted pollutants are nitrogen oxides (NO_x), carbon monoxide (CO), and unburnt hydrocarbons (UHC).

Pollutants are a result of incomplete combustion or poor combustion conditions allowing undesired compounds to form. The most important combustion parameters affecting pollutants formation are the equivalence ratio Φ (as defined by Eq. (2-9) in section 2.3), the temperature field in the combustion chamber, and the degree of mixing between fuel and oxidizer. Understanding the effect of these parameters on combustion emissions is essential to lowering the emissions.

Many combustion systems use air jets to minimize nitric oxides, carbon monoxide (CO) and unburnt hydrocarbons (UHC) emissions. Examples include fluidized bed combustors (using staged air injection), black liquor boilers, waste incinerators, gas turbine engines, and electric arc furnaces exhaust afterburners.

Additional experimental investigations are required to characterize the conditions under which pollutants formation takes place since for most industrial cases, efforts in modeling combustion have failed to predict accurately the levels of these pollutants. The nature of the interaction of jets with a reacting hot cross-flow is very complex. The outcome of the interaction is the result of the combined effects of mixing, turbulence,

chemical reaction, and heat release. In fact turbulence affects the reaction rate through the strain rate and the reaction rate affects turbulence through heat release and consequent density gradient. Rapid mixing accompanying the interaction between the jets and the cross-flow is crucial in minimizing emissions since it reduces the occurrence of pockets of mixture having an inappropriate equivalence ratio. Rapid mixing is even more important in applications where the combustor volume has to be kept as small as possible, such as gas turbine combustors.

The approach adopted to study the interaction between the jets and a hot reacting cross-flow is to first consider mixing in a non-reacting cross-flow. The findings for the non-reacting case can then be assessed for the case of jets in a reacting cross-flow. The mutual interaction between mixing and combustion efficiency can thus be evaluated using the non-reacting cross-flow findings as a reference.

1.2 Examples

Two major industrial applications this research relates to are electric arc furnaces and gas turbines.

1.2.1 Electric Arc Furnaces (EAF)

Electric arc furnaces are used extensively in the steel melting industry. Their primary function is to melt scrap steel as fast as possible. Figure 1-1 shows a schematic of an electric arc furnace. Electricity is the main energy source in the electric arc furnace. However chemical energy inputs are added. Current trends in the electric arc furnaces industry are towards the use of a larger proportion of chemical energy. In addition to

scrap steel, carbon and oxygen are injected into the steel bath to add additional energy and control the steel quality. A methane-oxygen burner is used to add more chemical energy in the furnace. The gas coming out of the furnace is rich in CO and H₂. Evenson et al. (1996) measurements showed that the concentration of CO and H₂ can reach concentrations of up to 25 % and 30 %, respectively. Carbon monoxide and hydrogen are burnt off by letting air enter into the exhaust duct through a gap. They must be consumed and the gases cooled down before reaching the bag house where flying ash is removed from the exhaust. It has been shown that gaps are a poor design solution to burn CO and H₂ contained in the off gases (Popovic et al. (1999)). The poor mixing effect of gap generates a long diffusion flame in the exhaust duct inhibiting efficient cooling. In addition, high CO and H₂ concentrations can reach the bag house increasing the risk of explosion. The introduction of air through discrete jets instead of the gap enhances the combustion efficiency of CO and H₂ by improving mixing.

1.2.2 Gas Turbines

Quick mixing is a key design parameter in advanced low NO_x gas turbines based on a rich-burn/quick-mix/lean-burn combustor. Quick mixing, for this particular application, reduces the occurrence of near stoichiometric pockets of mixture, therefore reduces NO_x production. In the first stage, fuel is burned at a rich equivalence ratio. In the dilution phase, air jets are used to quickly bring the overall equivalence ratio of the mixture to the lean zone. At this stage mixing must be as fast as possible to reduce the residence time at the stoichiometric equivalence ratio.

Figure 1-1: Steelmaking Electric Arc Furnace

1.3 Objectives

The main aim of this study is to improve the understanding of the relationship between mixing, chemical kinetics, and combustion efficiency for air jets in a hot reacting cross-flow. The study considers round jets of air issuing into a cylindrical cross-flow of hot fuel-rich gas as shown in Fig. 1-2. Many parameters are expected to have some influence on the combustion efficiency as determined by the level of CO and H₂ in the exhaust. The parameters considered here include the:

1. number of jets;
2. momentum flux ratio; and
3. the overall equivalence ratio.

To investigate the relationship between carbon monoxide destruction efficiency and mixing, measurements of unmixedness, based on carbon concentration, are undertaken. The study of the influence of chemical kinetics on the combustion efficiency is achieved by comparing the destruction efficiency of CO and H₂, two species with very different chemical kinetics properties.

Schematic of Modules Tested

Flow Configuration

Figure 1-2: Basic Geometry Studied

1.4 Outline of the Thesis

The thesis is divided into three main modules:

1. literature review;
2. experimental methodology; and
3. results and discussion.

The first section gives an overview of the research activity in the area of jets in non-reacting and reacting cross-flows. In addition, it places the contribution of this investigation in the context of the publications available in the field. The experimental methodology section describes the methodology adopted in the design of the experiments. The results as well as the conclusions of the study are presented in the results and discussion section.

2. Literature Review

The results of the investigations reported in this review are divided into three families: the dynamics of jets in a cross-flow, mixing of jets in non-reacting cross-flow, and mixing and combustion efficiency in jets in a reacting cross-flow. This division corresponds to the approach adopted in dealing with the complex problem of combustion in jets in a reacting cross-flow. Most of the results reported were obtained from the gas turbines literature, where the interaction between jets and cross-flows is extensively studied.

2.1. Dynamics of Jets in a Cross-Flow

The understanding of the basic flow structures created by the interaction between the jets and the cross-flow is essential to understanding mixing and combustion in jets in reacting cross-flows.

Carrotte et al. (1988) studied experimentally the flow structures in the dilution zone of a gas turbine combustor. They used a single round jet issuing into a cross-flow on a flat plate. Temperature and velocity were measured to map the structures that build up as the jet flows downstream. The jet issuing into the crossflow blocks the cross-flow fluid and causes it to accelerate through the free area not blocked by the jet. The flow immediately upstream of the jet decelerates creating an increase in pressure. Beneath the jet a rarefaction of the cross-flow fluid causes the pressure to drop. This pressure gradient between which the jet is caught causes it to bend downstream. A horseshoe vortex system associated with the deflection of the boundary layer, developed by the cross-flow on the flat plate, is detected. A second system of vortices, a stream-wise bound pair of vortices

at the sides of the jet is generated by the high velocity gradient in the radial direction. This pair gives the jet its characteristic kidney shape. The rate of its decay increases as the number of jets increases. A third system of vortices, called crossflow vortices, is generated by the cross-flow fluid passing between the jets. Figure 2-1 presents the schematic of the vortex structure generated by the interaction between the jet and the cross-flow. At low jet to cross-flow velocity ratio, the cross-flow was found to affect the flow upstream inside the pipe issuing the jet air into the cross-flow (Carrotte et al. (1988)).

Andreopoulos et al. (1984) also studied experimentally the same flow and observed the horseshoe vortex and the stream-wise double counter-rotating vortices. At low velocity ratios, the same effect of the cross-flow on the jet flow inside the pipe, observed by Carrotte et al. (1988), was observed by Andreopoulos et al. (1984). The horseshoe vortex effect is found to be small compared to the other vortices generated at the interface of the jet and the cross-flow.

The presence of the complex vortex structure resulting from the interaction between the jets and the cross-flow increases the mixing rate between the two streams. This provides motivation for the use of jets in a cross-flow as mixing flow configurations. The intensity and the structure of these vortices and thus mixing is affected by a series of flow and geometric parameters that are investigated in the following paragraphs.

Figure 2-1 Vortex Structure of a Jet in a Cross-flow Flow
 (from Carrotte et al. (1988))

2.2. Mixing in Non-Reacting Flows

Extensive research has been done to investigate jet mixing in non-reacting cross-flows. This research has been encouraged by the many industrial processes that involve jet mixing in a non-reacting environment. Further, since the interaction between jets and a reacting cross-flow is complex and involves the interaction of several phenomena (fluid dynamics, chemistry, and mixing), the investigation of the interaction between jets and a non-reacting cross-flow is a first step in approaching the problem.

The momentum flux ratio J was found to be an important flow parameter affecting mixing. It is defined as the ratio of the momentum of the jets to the momentum of the cross-flow by:

$$J = \rho_J * V_J^2 / (\rho_M * U_M^2) \quad (2-1)$$

where ρ_J , V_J and ρ_M , U_M are the density and the velocity of the jet and the main flow, respectively. The effect of flow conditions such as momentum flux ratio, jet to cross-flow density and velocity ratios; and cross-flow turbulence level on mixing and combustion efficiency is considered in the literature. The effect of geometrical parameters including jet spacing and jet diameter are also discussed.

2.2.1. Momentum Flux Ratio J , Reynolds Number and Turbulence

Intensity in the Cross-Flow

In an important summary article, Holdeman (1993) reports the major experimental and computational findings in the field of mixing of jets in a subsonic confined non-reacting cross-flow. The studies reported simulate the flow in the dilution

zone of the combustion chamber in a gas turbine engine. The objective of the studies was to identify dilution zone configurations providing the desired mixing pattern within a given combustor length. The optimum corresponds to the configuration giving the lowest unmixedness (i.e., best mixing) in a minimum downstream distance. The studies covered the following ranges:

- density ratio (jets over cross-flow), ρ_j / ρ_M : 0.5-2.2;
- downstream distance (measured in terms of multiples of duct height, H), x/H : 0-2;
- momentum flux ratio, J: 5-105;
- area ratio (total jets area over cross-flow area), A_j/A_M : 0.025-0.1; and
- mass flow rate ratio (jets total mass flow rate over cross-flow mass flow rate), m_j / m_M : 0.075-0.36;

The primary parameters investigated are, the momentum flux ratio, the jet to mainstream density ratio, jet diameter d and jet spacing s . The mixing is found to improve with increasing downstream distance. The studies show that the momentum flux ratio is the most important parameter affecting mixing. The studies show that there is an optimum J, J_{OPT} , yielding the best mixing for each jet configuration tested. Smaller or higher values of J require much longer downstream distances to achieve similar mixing.

For each jet configuration, jet penetration depends on the value of J. Three situations can arise (Fig. 2-2):

- **Under penetration:** occurs when J is too low. Jet fluid stay near the walls of the cross-flow pipe;
- **Over penetration:** occurs at high values of J . In this case, the jets impinge in the center of the duct. Back flow occurs if J is high enough.
- **Optimum penetration:** occurs when $J=J_{OPT}$. At this value of J , the centerline of the jets reaches the radius dividing the section of the pipe into two equal areas.

Doerr et al. (1995) carried out an experimental investigation to determine the flow and geometric conditions that achieve rapid and intense mixing of multiple jets in a non-reacting heated cross-flow. A row of opposed-jets was injected in a heated rectangular cross-flow. Spacing and jet diameter were varied. The total discharge area of the jets was kept constant. Mixing was measured based on temperature profile. For each of the configurations tested, the momentum flux ratio was varied up to $J=200$. The experiments show that J has an important impact on mixing. For each of the configurations tested, there is an optimum J yielding an optimum mixing. For J exceeding the optimum value, mixing decreases as a result of the interaction between the opposed-jets and the consequent thermal stratification of the flow field. The three dimensional flow becomes two-dimensional. A back flow is also observed for high J values. For $x/d>1$, the temperature profiles are similar for all the configurations, where x and d are the distance of the plane of measurement from the plane of injection of the jets and the diameter of the jets, respectively.

Figure 2-2 Jet Penetration Depending on the Value of J

Holdeman et al. (1996) present an extensive review of NASA supported investigations regarding mixing of a row of jets in a subsonic cylindrical cross-flow. Both reacting and non-reacting flows are reported. These investigations were performed for jet to cross-flow mass-flow ratio, and jet to cross-flow area ratio A_J/A_M smaller than 1 and 0.5, respectively. The jet orifices studied are thin (thickness/diameter < 0.25). The observations reported in Holdeman et al. (1996) include: the effect of the number of jets at constant J , the cross-flow diameter, the relation between mixing and emissions, and the effect of J . Penetration of the jets is found to be an important factor in mixing. As discussed earlier, it decreases with decreasing J .

Blomeyer et al. (1999) examined, experimentally, mixing in a non-reacting slightly heated rectangular cross-flow. One row of opposed round jets in both in-line and staggered arrangements was tested. Density ratio in the test was equal to 1.1 (in real gas turbines it is about 3). Carbon dioxide (CO_2) was injected in the crossflow to test the accuracy of the assumption of the analogy between heat and mass transfer. The cross-flow mass flow rate was kept constant while J , s/d , and H/d were varied. The momentum flux ratio was varied within the range of 5 and 300. The cross-flow turbulence intensity and the Reynolds number were varied from 1% to 8% and 25,000 to 55,000, respectively. They found that mixing is not affected by the cross-flow Reynolds number and turbulence intensity. Instead, swirl in the cross-flow was found to have a major effect. The profiles of temperature and CO_2 are found to be identical. Therefore heat transfer can be used to trace mass transfer and hence mixing. The momentum flux ratio was increased until minimum unmixedness was reached. No experiments where the jets back-flow were carried out since this situation does not apply to the Rich burn/Quick mix/Lean burn

combustors. For staggered jets, the strong shear layer improves mixing as J increases. No optimum J was observed and mixing remains at its best if J continues to be raised. Crossflow swirl improves mixing and, due to lateral motion that shifts the jets, reduces jet penetration. Therefore optimum mixing occurs at a higher J when swirl is present.

2.2.2. Number, Spacing, Diameter and Penetration of Jets

As discussed by Holdeman (1993), the diameter of the jets does not affect mixing or jet penetration (Holdeman et al. (1996)), when the number of jets is kept constant and the mass flow ratio is adjusted to keep the momentum flux ratio constant. However, for constant J , Holdeman et al. (1996) observed a decrease in jet penetration as the number of jets is increased. Increasing the jet spacing s , at constant J and H , increases penetration but decreases lateral uniformity (Holdeman (1993)). For the same area ratio A_J/A_M (constant total area of the jets), jets with smaller individual area under-penetrates, while a configuration with higher jet individual area tends to over-penetrates. Computational fluid dynamics models reproduce the previous trend, although the mixing is underestimated due to the underestimation of turbulence intensity by the $k-\epsilon$ turbulence model (Holdeman (1993)). Hatch et al. (1995b) showed that optimum mixing occurs when the jet trajectory is at 50 to 65% from the duct centerline at one radius downstream.

Doerr et al. (1995) also showed that s/d significantly affects the temperature profile. They also observed that the higher the number of jets, the higher the optimum J is. Larger jet spacing requires longer downstream distance to achieve optimal mixing.

For in-line jets, Blomeyer et al. (1999) observed that, at $x/H=0.25$, the best mixing occurs when jets penetrate to the middle of the mixer height, without impinging. Values of J that are smaller or higher than the optimum yield under or over penetration,

respectively, leading to poor mixing. Jet diameter was found to have a non-negligible effect on mixing, especially for staggered jets, which is apparently contradictory to what Holdeman (1993) reported. This emphasizes the importance of the range of the investigations since they limit the scope of the validity of the conclusions.

The references agree on the importance of jet spacing (thus number of jets) and penetration on mixing quality. Jet diameter can have an effect on mixing depending on the range momentum flux ratio at which the mixing occurs. Section 2.2.4., on correlations for optimum mixing, evaluates this effect.

2.2.3. Density Ratio

The effect of density ratio is considered to be negligible at constant momentum flux ratio. Its effect has only a second order influence on jet penetration and profile shape. The momentum flux ratio J incorporates the ratio of the densities, thus accounts for any variation in this ratio (Holdeman (1993)).

2.2.4. Correlations for Optimum Mixing

Numerous correlations based on experimental and empirical models have been proposed to predict mixing. Holdeman's correlation is the most frequently reported in the literature.

According to Holdeman (1993) and Holdeman et al. (1996), when the momentum flux ratio, J , and the relative spacing, s/H , remain inversely proportional, temperature profiles show similar distributions over a range of J . When the spacing increases (momentum flux ratio decreases) the circumferential unmixedness increases. Jet

penetration and centerplane profiles are similar when they satisfy the following the relation (Holdeman (1993)):

$$\sqrt{J} * (s / H) = C \quad (2-2)$$

where C is a constant.

Experimental and calculated data show, for single sided injection in a rectangular cross-flow, that there are three flow regimes depending on the value of the constant C (Holdeman (1993)):

- C=2.5: mixing is obtained in the minimum downstream distance;
- C<1.5: Jets under-penetrate. Jet fluid remains close to the duct wall; and
- C>5.0: Jets over-penetrate. Jet fluid concentrates in the center of the duct.

In terms of spacing, optimum momentum flux ratio J_{OPT} is given by:

$$J_{OPT} = 6.25 * (H / s)^2 \quad (2-2b)$$

Blomeyer et al. (1999) propose the following correlation for the optimum momentum flux ratio, J_{OPT} , at $x/H=0.5$ in the case of in-line double sided injection of round jets in a rectangular crossflow:

$$J_{OPT} = 0.045 * (H / d)^2 + (3.08 + (H / d)^{1.65}) / ((s / d) + 0.26)^{1.29} \quad (2-3)$$

for staggered jets, they suggest the following correlation:

$$J_{OPT} = 25 * (H / d)^{0.6} * (1 + 0.6 * ((s / d) - 0.23 * (h / d))^{-1.6}) \quad (2-4)$$

Blomeyer et al. (1999) report that Eq. (2-2) was developed for single sided injection in a rectangular crossflow. Two-sided injection was expected to be similar to

single sided injection if instead of H , $(H/2)$ is used in Eq. (2-2). This assumption leads to $C=1.25$ for double sided opposed jets. For staggered jets, optimum mixing occurs when the jets penetrate past each other. The assumption is that the optimum occurs when the spacing is double the optimum spacing for the single sided injection with the same total number of jets. Furthermore Eq. (2-2) was derived under the following conditions: mass flow ratio < 0.5 (for RQL combustor, mass flow ratio > 2.0) and $J < 100$.

The duct height H in Eq. (2-2) corresponds to the duct radius R in a cylindrical duct (Holdeman et al. (1996)). As discussed by Holdeman (1993), for a rectangular cross-flow and a single sided injection, at the optimum mixing, the centerplane profiles are centered across the duct height. Optimum spacing in Eq. (2-2) is specified at mid height of the duct (dividing the duct section into two equal areas). The mid area radius that divides the section into equal areas for a cylindrical duct is situated at a radius $R_{1/2}$:

$$R_{1/2} = R / \sqrt{2} \quad (2-5)$$

Relating the number of jets n to the spacing s at this radius ($R_{1/2}$) gives:

$$s = 2 * \pi * R_{1/2} / n \quad (2-6)$$

Substituting (2-3) into (2-4) yields:

$$n = \pi * \sqrt{2 * J} / C \quad (2-7)$$

In terms of the number of jets n , J_{OPT} is given by:

$$J_{OPT} = 0.32 * n^2 \quad (2-8)$$

Hatch et al. (1995a) found that J is the most important parameter affecting the flow field. They tested an 8 round jets module, issuing air into a non-reacting cylindrical cross-flow, for values of momentum flux ratio equal to 26.7, 55.4, 84.2, respectively. Equation (2-8) predicts the optimum momentum flux ratio to be equal to 19.2. The first value tested (26.7) yielded the best mixing since it is the closest to the optimum.

Although the correlation of Blomeyer et al. (1999) has a larger range of validity for the momentum flux ratio and mass flow rate ratio, it has the disadvantage that there was no version of it for the cylindrical geometry. Thus, Eq. (2-8) will be used as design guideline for the modules to be tested. This will allow the assessment of the effect of mixing on combustion efficiency.

2.3. Mixing and Combustion Efficiency in Reacting Cross-Flows

Even though the investigations have been successful in developing correlations to predict optimum mixing conditions for jets in non-reacting cross-flows, there are still no correlations available to predict optimum combustion conditions for jets in a reacting cross-flow. The complexity of the interaction between mixing, fluid dynamics, chemical kinetics and heat release makes such correlations very difficult to elaborate. The investigations reported by Holdeman et al. (1996) suggest that it is unlikely that research in this field will lead to a universal “rule of thumb” for low emission systems design. The cold flow correlations are thus usually used as a guideline when studying the emissions from jets in a reacting cross-flow system.

In addition to the usual flow conditions affecting mixing in a non-reacting cross-flows, the effect of the equivalence ratio Φ is also investigated for the reacting cross-flows. The equivalence ratio Φ is defined by:

$$\phi = (m_F / m_A) / (m_F / m_A)_s \quad (2-9)$$

where (m_F / m_A) and $(m_F / m_A)_s$ are, respectively, the actual and stoichiometric fuel to air mass flow rate ratio.

2.3.1. Effect of Momentum Flux Ratio and Flow Geometry

The computational fluid dynamics work of Talpallikar et al. (1990) to model the RQL gas turbine combustion chambers has shown that there is an optimum J that yields the best mixing, the same trend as in the case of non-reacting cross-flows. They observed that jet penetration increases as the number of jets decreased, for a constant momentum flux ratio equal to 36. Fourteen jets under-penetrated whereas ten jets over-penetrated and generated back-flow. Optimum mixing was observed for 12 jets. This is very close 11 jets, the optimum predicted by Eq. (2-2) for non-reacting flows.

The computational work of Smith et al. (1991) investigated the effect of the cross-flow diameter on mixing and NO_x emissions. A twelve jets geometry was used. Four, five and six inch cross-flow diameters were investigated. A reduction of the cross sectional area of the cross-flow caused the velocity of the cross-flow to increase. This was accompanied by a drop in the cross-flow static pressure. The drop in the cross-flow pressure increased the pressure drop across the jet orifices causing the jets to accelerate. These increases in velocity were offsetting such as J remained constant. The jets section were adjusted to maintain a constant mass flow rate ratio. The mixing patterns for the three diameters were found to be similar. However, nitrogen oxides concentrations for the three diameters were different. The NO_x levels increased as the diameter of the cross-flow increased. Nitrogen oxides level is a function of local species concentrations,

temperature, and residence time. Mixing was similar for the three diameters, therefore species concentration and temperature fields are similar. Thus residence time is the factor accounting for the difference in NO_x level. It has also been observed that the bulk of NO_x formation occurs early in the mixing stage. This makes early mixing processes critical in determining NO_x emissions. This leads to the conclusion that although mixing is a key parameter affecting pollutant emissions level, it is not the only determinant factor to be taken into account.

Hatch et al. (1995b) showed that there is no apparent correlation between statistical parameters characterizing mixing and NO_x production rates since planar variances don't include historical information about the flow. This is in agreement with the previous investigation of Smith et al. (1991) where the residence time was found to have a decisive effect on NO_x levels. They also noticed that NO_x levels are highly affected by jet penetration. Both under and over-penetrating jets yielded high NO_x levels. This is due to the effect of mixing; over and under penetrating jets deteriorate mixing increasing consequently NO_x emissions. Therefore optimum mixing doesn't result in minimum NO_x emissions, since other factors such as residence time affect NO_x levels.

Leong et al. (1999) undertook experiments simulating the quick quench in a gas turbine primary zone. Round jets issuing into a hot reacting cylindrical crossflow were used. Temperature, O_2 , CO_2 , CO and unburnt hydrocarbons (UHC) concentrations were measured. Jet penetration, mixing and species concentration were measured for a 10 round jets configuration operated at a momentum flux ratio and mass-flow ratio equal to 57 and 2.5, respectively. The bulk of the reaction and mixing occurs within one duct

radius downstream of the jets leading edge. Additional mixing occurs up to one diameter downstream.

For a reacting cylindrical cross-flow, Leong et al. (1995) found that the jet penetration affects mixing and is a function of the number of jets. At constant $J=57$, eight, nine, ten and twelve round jets were used. The twelve round jets produced the best mixing at one duct radius downstream of the jets leading edge. This is close to 13 jets, the optimum predicted by Eq. (2-2) for non-reacting flows. Jet penetration for this case was the closest to the duct half radius. For 8, 9 and 10 jets cases, jets over-penetrate. Jet air concentrates in the middle of the mixer instead of spreading radially and mixing with fuel.

Oechsle et al. (1995) used a three dimensional model to predict mixing and nitric oxide levels in the case of air jets entering into a reacting cylindrical cross-flow. The model simulates nitric oxide production and mixing in the mixing section of an RQL combustor. Three parameters were varied during the study: jet to mainstream momentum flux ratio, orifice aspect ratio and slot slant angle. Mixing and NO_x level were evaluated at $x/R=1$. Mixing and NO_x concentration are strongly affected by jet penetration. At high momentum flux ratios, NO_x level was efficiently reduced by slanting elongated slots. Due to their stronger penetration, the round jets lower NO_x concentrations at low J . Over and under-penetrating jets displayed increased NO_x concentrations. Similar to other authors cited in this section, they found that the data showed no correlation between mixing and NO_x concentration since parameters other than mixing affect NO_x emissions. Oechsle et al (1994) compared temperature distribution, for non-reacting flows, with normalized equivalence ratio distribution for reacting flows. The results of the investigation suggest

that temperature profiles, in non-reacting flows, emulate equivalence ratio distribution in corresponding reacting flows. This means that, for the same flow conditions, there is a resemblance in the mixing patterns between reacting and non-reacting flows.

Recently, Popovic et al. (1999) investigated the effect of J and orifice geometry on CO emissions for air jets injected into a hot, fuel rich cross-flow. They investigated five configurations: two circumferential slots, 4 round jets, 9 round jets, and 4 streamlined slots (aspect ratio 4:1). The measurements of CO were done at 48 diameters downstream of the plane of injection of the jets where the reaction and the mixing are assumed to be complete. The optimum combustion efficiencies, for four and nine round jets, were found to occur at momentum flux ratios that correspond to optimum mixing as predicted by Eq. (2-8). Discrete openings had a higher combustion efficiency than the circumferential slots for all values of J . For the same number of jets, and the same value of J , round holes and streamlined slots exhibited the similar performance. The modules tested were designed such as the momentum flux ratio and the equivalence ratio are coupled. The momentum flux ratio and the equivalence ratio were coupled during the experiments too. For each of the modules tested there was an optimum momentum flux ratio J_{OPT} yielding the lowest CO concentration. Of all the modules tested, the 9 round jets configuration provided the best CO destruction at all values of J .

The review shows that the momentum flux ratio plays an important role in reacting flows. An optimum momentum flux ratio yielding optimum mixing exists also for reacting cross-flows. The literature also shows that Eq. (2-2) derived initially for non reacting cross-flow can be used to approximate the value of the momentum flux ratio yielding optimum combustion efficiency although it is not accurate in all cases. Factors

other than mixing have to be taken into account for reacting cross-flows. Residence time for NO_x production is one such parameter.

2.3.2. Effect of Equivalence Ratio

In terms of degree of mixing of fuel and oxidizer before the combustion takes place in the system, there are two limit cases of combustion systems:

1. Non-premixed systems, where the fuel and the oxidizer are not mixed and the combustion occurs at the interface.
2. Premixed systems, where the fuel and the oxidizer are perfectly mixed before the combustion takes place.

The relative values of the mixing time scale and the chemistry time scale are of major importance in determining the regime of combustion. Infinitely fast mixing systems have premixed combustion. In contrast, infinitely fast chemistry produces non-premixed combustion. In real combustion configurations, like jets in a crossflow for instance, the time scales of mixing and chemical reaction are finite. Thus partial premixing takes place between fuel and oxidizer before combustion occurs. The equivalence ratio has no relevance for strictly non-premixed reacting flows, but has a role in totally or partially premixed reacting flows.

The laminar premixed flame is a classic limit case of fast mixing and slow chemistry. Stahl et al. (1991) investigated numerically laminar premixed flames with time-dependant strain rate and pressure. The model included detailed chemistry. The interest of the study was to gain insight into the processes involved in unsteady turbulent combustion systems where turbulent flowfield and pressure are time variant. They looked

at the extinction limits, in terms of strain rate, of the methane-air flames at different equivalence ratios. The results of the simulations using a C-1 and C-3 chemistry mechanisms were compared to experimental measurements and other numerical simulations using mechanisms including C-1 and C-2 species. They show that the curve of the strain rate, at extinction limit, versus equivalence ratio displays a maximum for an equivalence ratio between 0.8 and 1.0. Thus as the equivalence ratio decreases, the strain rate at which extinction occurs also decreases. The extinction limit decreases also when the equivalence ratio increases.

A well-stirred reactor is a representation of the complete premixing limit. Zelina and Ballal (1997) studied CO emissions in a well-stirred reactor. A toroidal well-stirred reactor was used to measure combustion efficiency, combustion stability under lean conditions, and CO emissions. Two fuels were used, propane and a hydrocarbon blend made of methane, ethane, and ethylene. The well-stirred reactor was operated at equivalence ratios varying from 0.4 to 2.5. The study focused on the fuel lean condition and the residence times of 2.5 ms and 12 ms. The mixing time is estimated to be in the range of 0.1 ms. Due to the high mixing efficiency in the well-stirred reactor, the combustion efficiency, thus emissions level, is controlled primarily by the reaction rate and the equivalence ratio. It was found that CO emissions display a minimum around the equivalence ratio 0.6 (for temperatures in the combustion zone of 1600 K), which is in agreement with what was measured in a real gas turbine combustor (Zelina and Ballal (1997)). Carbon monoxide emissions increase for equivalence ratios leaner than 0.6, as a result of cold air quenching and too low temperatures in the combustion zone. For

equivalence ratios richer than 0.6 CO quickly increases because of the local unavailability of enough oxygen to complete the oxidation of CO.

The behavior of a gas turbine combustor, where air jets are used to quickly quench the rich mixture leaving the primary zone, resembles the behavior of well-stirred reactors. Rizk and Mongia (1993) examined the emissions of CO, NO, and unburnt hydrocarbons from a gas turbine engine. The presence of carbon monoxide in the exhaust is an indication of inadequate burning rates, insufficient mixing, short residence time, or quenching due to low temperatures. A model was developed consisting of a series of reactors simulating the processes in a real combustor. The primary zone is simulated by two series of parallel reactors, representing the near-wall and the core regions, respectively. The output of the two series of reactors merges to flow through a single plug flow reactor. Air is injected in the different reactors according to the corresponding injections of air in the real gas turbine combustor. The effect of the equivalence ratio and the residence time, amongst other parameters, was investigated. The results of the model showed good agreement with measurements taken in a real gas turbine combustor. Carbon monoxide concentration in the exhaust were minimized around Φ equal to 0.7. They found that for high equivalence ratios (higher than 0.7), the concentration of CO in the exhaust decreases as Φ is reduced. For lower equivalence ratios (lower than 0.7), CO concentration increases when decreasing Φ .

The review suggests that combustion efficiency of jets in a reacting cross-flow is affected by the equivalence ratio. This suggests that some partial premixing occurs in these flows.

2.4. Summary

The literature reviewed suggests that the main factor affecting mixing for jets in a non-reacting cross-flow is the momentum flux ratio. The investigations were successful in deriving correlations to predict optimum geometrical and flow conditions yielding optimum mixing. Caution is needed when applying these correlations. The ranges of the parameters, that were used to derive them, limit the scope of their validity. The correlation of Holdeman as given in Eq. (2-8) will be used in this study as a guideline in the design process.

Although the momentum flux ratio is still an important factor affecting the combustion efficiency for jets in a reacting cross-flow, it is not the only parameter. Other parameters such as the residence time and the equivalence ratio are important parameters affecting combustion efficiency. This multiplicity of parameters has prevented researchers from deriving appropriate correlations. Thus non-reacting cross-flow correlations are often used as a guideline in the study of reacting cross-flows.

3. Experimental Methodology

The predictions from cold flow theory were used as a guideline during the design of the experiments to select the configurations to be tested. For each geometric configuration tested, both the equivalence ratio and the momentum flux ratio can be varied by varying the mass flow rate ratio.

3.1. Experimental Apparatus

The experimental apparatus used for the current work has been previously described by Popovic et al. (1999). The apparatus consists of two main modules, the primary reactor and the mixing module (Fig. 3-1). This experimental setup was initially designed to investigate the use of jets to improve the CO and H₂ destruction efficiency in off-gases originating in an electric arc furnace. In addition to the modules used in the previous study, new mixing modules were tested to decouple the effect of the momentum flux ratio and the equivalence ratio. Furthermore a new eighteen round jets module was used to investigate the high range of number of jets. The function of the primary reactor is to produce hot gases rich in CO and H₂. Natural gas is used as the primary fuel. It is mixed with ambient air at an equivalence ratio, ϕ_M , of 1.5. The total mass flow rate that is injected in the reactor is 3.5 g/s. Two Hastings HFC-203 mass flow controllers are used to set the mass flow rate of air and natural gas burning in the reactor. At the exit of the reactor the hot gases pass through a ceramic foam matrix plug to reduce the velocity, temperature and concentration gradients. The Reynolds number of the cross-flow at the mixing module inlet is 4000. The cross-flow is confined in a 25 mm inner diameter

metallic duct. After the plane of the injection of the jets the flow continue inside a quartz tube of the same diameter.

The air jets enter the cross-flow in the mixing module (Fig. 3-2). The secondary air (air entering through the jets), first passes through the plenum, before being injected in the cross-flow. The plenum chamber acts as a stabilizer of the air before supplying the jets. Two quartz glass plenums were used, depending on whether the measurements in the exhaust pipe are to be taken at 48 or 1.5 diameters downstream. The lengths of the two plenums are 305 mm, and 125 mm, respectively. The inner diameter of the plenum is 95 mm. The secondary air mass flow rate was varied from 1.2 g/s to 5.4 g/s. A Hastings HFC-203 mass flow controller was used to adjust the secondary air mass flow rate. Table 3-1 gives the characteristics of the jets tested, and the experiments carried out for each of them. The temperature of the hot gases exiting the reactor, the secondary air, and the exhaust leaving the quartz tube are monitored using thermocouples.

The resulting overall equivalence ratio Φ in the cross-flow after the injection of the jets varies between 0.5 and 1.1. The 'overall equivalence ratio', Φ , includes both air injected in the primary reactor and through the jets. It is given by:

$$\Phi = [n_{MF} / (n_M + n_I)] / (n_F / n_A)_s \quad (3-1)$$

where n_M , and n_{MF} are the molar flow rate of air and methane, respectively injected in the primary reactor; n_I is the molar flow rate of jet air; and $(n_F/n_A)_s$ is the molar stoichiometric ratio of methane and air.

Figure 3-1 The Experimental Facility

Figure 3-2 The Mixing Module

Configuration name	Number of Jets	Diameter of Jets (mm)	Optimum J predicted by Holdeman	Range of Reynolds number of the exhaust flow	Range of Reynolds number of the jets	Range of J	Measurements taken for the module
4RJ	4	7	5	7,200-13,800	4000-10,700	2- 12	CO and H ₂ at x/D=48.
9RJ _a	9	3.18	26	7,300-13,000	4,000-10,000	4- 87	CO at x/D=48.
9RJ _b	9	3.97	26	7,400-13,300	3,200-8,300	52- 456	CO at x/D=48.
9RJ _c	9	2.05	26	7,300-13,300	6000-16,100	53- 525	CO at x/D=48.
9RJ _d	9	2.64	26	7,300-13,300	4,700-12,500	16- 156	CO at x/D=48.
9RJ _e	9	2.37	26	7,300-13,300	5,200-13,900	23- 315	CO at x/D=48.
9RJ _f	9	2.85	26	7,300-13,300	4,300-11,600	12- 87	CO at x/D=48.
9RJ _g	9	2.5	26	7,300-13,300	4,800-13,100	25- 313	CO at x/D=48.
18RJ	18	1.59	104	6,000-13,000	1,900-13,000	20- 309	CO and H ₂ at x/D=48, and CO and CO ₂ at x/D=1.5.

Table 3-1 Jet Configurations Tested

3.2. Measurement Techniques

3.2.1. Carbon Monoxide Concentration Measurements

Two analyzers were used to measure the concentration of CO. They both have a pump incorporated in them. The pump ensures the flow of the sample from the point of measurement to the analyzing module. For low ranges of CO concentrations (concentrations below 4 %), a NOVA 362WP gas analyzer with a chemical cell was used. The analyzer has two ranges: a high and a low range. The low and high range cover the intervals 0 to 1999 ppm and 0 to 4 % CO, respectively. In addition to carbon monoxide, the analyzer also measures the oxygen and the total nitrogen oxides concentration in the exhaust. For high ranges of CO concentration measurements (between 4 and 10 %), carbon monoxide concentrations were measured using a NOVA infrared detector model 7800P2-A. The equipment measures CO in the range 0-10 %. The equipment also measures carbon dioxide concentrations in the same range. The error analysis regarding carbon monoxide measurements is presented in section 3.3.1. of this chapter.

Prior to each experiment the analyzers were calibrated using a calibration gas. For the Nova 362WP, a calibration gas with 1076ppm carbon monoxide balanced with nitrogen was used. For the Nova 7800P2-A, a mixture of 9.01% carbon monoxide and 9.00 % carbon dioxide balanced with nitrogen was used for calibration.

Two types of sample extracting probes were used: a steel water-cooled probe and a quartz glass probe. The water-cooled probe has a coarse outer diameter of 5 mm (for a cross-flow diameter of 25 mm), thus not allowing 'fine' spatial gradients. The cooling of the probe is necessary to freeze the oxidation of carbon monoxide and hydrogen at the

actual level existing at the point of measurement in the exhaust and prevent any further reaction along the sampling line. The quartz glass probe has an outer diameter of 1.4 mm. It, thus, allows finer spatial gradients measurements, although it does not freeze the reactions in the sample. This probe was used for the measurement of carbon monoxide and carbon dioxide concentrations for the purpose of evaluating the unmixedness based on the total carbon concentration. In this situation carbon monoxide oxidation into carbon dioxide is not a concern.

3.2.2. Hydrogen and Methane Concentration Measurements

Hydrogen measurements were made using a Gas Chromatograph (GC). A Supelco 2-5461 Carboxen 1006, 30 mm x .53 mm Plot column was used to separate the species in the sample. The sample is injected at one end of the column. A carrier gas flowing through the column carries the sample across the column. On their way from one end of the column to another, the species contained in the sample diffuse in and out of the medium layering the inner wall of the column. The time taken by each of the species to come out of the column (the retention time) depends on the coefficient of diffusivity of the species in the medium. The difference in the retention time for the species contained in the sample determines the ability of the column to separate the sample. The samples contain H_2 , CO, CO_2 , O_2 , N_2 , and traces of CH_4 . The column that was used separates all these species.

A Thermo Conductivity Detector (TCD) was used to detect the concentration of the species separated in the column. The thermal conductivity of the flow coming out of the column depends on the properties and the concentration of the species coming out.

The conductivity of the mixture of the species and the carrier gas (nitrogen for this study) is compared to the baseline conductivity of the carrier gas. The difference between the two conductivities is proportional to the molar fraction of the species in the carrier gas. Therefore, the key parameter in choosing the carrier gas is its conductivity. This conductivity has to be different from the conductivity of the species that need to be detected. Table 3-2 (From Robert et al. 1979-1980) gives the thermal conductivity of the species present in the samples. The values of the conductivities show that nitrogen is a suitable carrier gas for measuring hydrogen and methane.

The error analysis made for the hydrogen measurements is discussed in section 3.3.2. of this chapter.

3.2.2.1 Gas Chromatograph Calibration

Prior to conducting the measurements using the gas chromatograph, a test was carried out to choose the pressure and temperature conditions that give the best separation of the sample. For this test, a sample from the exhaust gas was used. After selecting the operating conditions, the calibration of the GC was performed. The first step in the calibration process was determining the retention time for each of the species present in the samples. The second step was determining the calibration curves for hydrogen and methane. The operating parameters of the GC as well as the retention times for H₂, CH₄, CO, CO₂, and O₂ are given in Table 3-3. Carbon monoxide and oxygen have retention times of 1.08 min and 1.07 min, respectively. Therefore the column is not suitable for separating O₂ and CO. Methane and hydrogen are well separated by this column since they have retention times that do not overlap with any other species.

	H₂	CO	CO₂	O₂	N₂	CH₄	He
Thermal Conductivity at 48.9 °C (Cal/ .Cm².(°C/Cm)	471.11	63.89	43.81	68.19	65.71	89.26	376.07

Table 3-2 Thermal Conductivity of the Carrier and the Species Present in the Samples

Species	H₂	CH₄	CO	CO₂	O₂
Retention Time (min)	.91	1.98	1.08	4.95	1.07
Standart Deviation (retention time)	.01	.01	.01	.01	.00

Table 3-3 Retention Times of the Species

For the following operating conditions:

Pressure: 3 psig

Temperature: 32 °C

Run Time: 5.3 min

The GC was used to measure H_2 and CH_4 . Hydrogen was measured at 48 diameters downstream; and upstream of the plane of injection of the jets. Methane was measured upstream of the jets to verify that all the methane was practically burnt in the primary reactor. Hydrogen calibration was performed in two ranges. Eight samples were used to calibrate in the 0-10 % H_2 range for the measurements upstream of the jets. Figure 3-3 shows the calibration data. For the measurement of hydrogen at 48 diameters downstream, the gas chromatograph was calibrated for the range 0-2 % H_2 . Six samples were used for this purpose. Figure 3-4 shows the calibration curve for this range of hydrogen concentration. Six samples were used to obtain the methane calibration curve in the range of 0-8 % as shown in Fig. (3-5).

3.2.2.2 Samples Preparation for GC Measurements

Samples were taken using a series of flow-through quartz glass gas samplers equipped with a septum. The volume of the samplers is 250 ml. The sample is taken after dehumidification and quenching of the exhaust gas. The samples are immediately pressurized by injecting an additional 2 ml nitrogen in the tube samplers. Each sample is injected 3 times in the column. Figure 3-6 presents the tube samplers used. The water-cooled probe was used to extract and quench the samples at both 48 diameters downstream and one diameter upstream locations.

**Figure 3-3 Hydrogen Calibration Curve
(for measurements 48 diameters downstream)**

Figure 3-4 Hydrogen Calibration Curve
(for measurements upstream of the jets)

Figure 3-5 Methane Calibration Curve

Figure 3-6 Tube Sampler

3.2.3. Unmixedness Measurements

The unmixedness calculations were based on the total carbon mole fraction, defined for this study as the sum of the CO and CO₂ mole fractions. Carbon monoxide and carbon dioxide mole fractions were measured using a NOVA infrared detector model 7800P2-A described in section 3.2.1. of this chapter. The equipment measures both CO and CO₂ in the range 0-10 %. The quartz probe was used to extract the sample.

The measurements of CO and CO₂ were made at 50 locations chosen using a random number generator to allocate the coordinates. The section of the cross-flow is divided into 10 sectors I (Fig. (3-7)). Each sector I is delimited by two concentric circles having the radiuses R_I and R_{I+1} , respectively. The radiuses R_I take the values: 1.2, 1.4, 3.6, 4.8, 6, 7.2, 8.4, 9.6, 10.8, and 12.7. Each sector I (I=1 to 10) has the A_I given by:

$$A_I = \pi * (R_{I+1}^2 - R_I^2) \quad (3-3)$$

The total area A is given by:

$$A = \pi * R_{10}^2 \quad (3-4)$$

The number of points of measurement that fall into a sector I is designated by n_I . A probability value P_I is associated to each measurement point located in the sector I. The value of P_I is given by:

$$P_I = (1 / n_I) * (A_I / A) \quad (3-5)$$

Figure 3-7 Division of the Section

The unmixedness is evaluated using the same expression used by Vranos et al. (1991):

$$\Sigma = \sigma / \mu \quad (3-6)$$

where Σ , σ , and μ are the unmixedness, the standard deviation of the total carbon molar fraction, and the mean value of the total carbon molar fraction, respectively. A low value of unmixedness indicates that the fluid is well mixed across a pipe cross-section. A high value of unmixedness implies that large gradients in species concentration exist.

As presented in Moore et al. (1999), for a discrete variable X (total carbon molar fraction for the present case) taking the possible values $x_1, x_2, \dots, x_K$ with the probabilities $p_1, p_2, \dots, p_K$, respectively, the mean μ_X is given by:

$$\mu_X = \sum_{I=1}^{I=K} x_I * p_I \quad (3-7)$$

The variance σ_X^2 of the variable X is given by:

$$\sigma_X^2 = \sum_{I=1}^{I=K} (x_I - \mu_X)^2 * p_I \quad (3-8)$$

These two formulas were used to evaluate the mean and the variance of the total carbon molar fraction in the cross-section.

3.3. Design of Experiments

The total mass flow rate m_M of the cross-flow was kept constant and equal to 3.50 g/s for all the experiments. The equivalence ratio Φ_M in the primary reactor is also kept constant and equal to 1.5 throughout all the experiments.

The diameters of the jet configurations for the 4RJ, 9RJ_a and 18RJ modules were chosen such that the optimum momentum flux ratio predicted by Eq. (2-8) would occur when the secondary air mass flow rate is equal to the cross-flow mass flow rate (in agreement with the operating conditions of electric arc furnaces). Under these conditions, the overall equivalence ratio is equal to 0.8. The diameters of the jets for the 9RJ_b, 9RJ_c, 9RJ_d, 9RJ_e, 9RJ_f and 9RJ_g modules were chosen to have an overall equivalence ratio of 0.63, 1.13, 0.97, 1.04, 0.92 and 1.01, respectively, when the momentum flux ratio is equal to the optimum predicted by Eq. (2-8), which is equal to 26 for a 9 round jets module. This decouples the momentum flux ratio and the equivalence ratio allowing the study of the momentum flux ratio at a constant value of the equivalence ratio.

In order to properly evaluate combustion efficiency, the effect of dilution on CO and H₂ molar fractions in the exhaust must be considered. The diluted molar fraction of CO and H₂ was evaluated for each measurement. The actual molar fraction of both CO and H₂ measured in the exhaust was compared to the diluted molar fraction rather than comparing it to the initial molar fraction of CO and H₂ in the cross-flow before the injection of the jet air. The diluted molar fraction, for CO, is defined as:

$$[CO]_D = [CO]_I * n_M / (n_M + n_I) \quad (3-2)$$

where $[\text{CO}]_I$ is the initial value of the carbon monoxide molar fraction in the cross-flow before mixing with the jets; and n_M and n_J are the molar flow rates of the cross-flow and the jets, respectively. The hydrogen diluted molar fraction $[\text{H}_2]_D$ is calculated in the same way.

3.3.1. The Effect of the Number of Jets and the Coupled Effect of the Momentum Flux Ratio and the Equivalence Ratio

The effect of the number of jets was carried out by testing the 4RJ, 9RJ and the 18RJ. These configurations have different non-reacting flow optimum mixing momentum flux ratio, J_{OPT} , given by Eq. (2-8) (see Table 3-1). The 4 round jets with a J_{OPT} of 5 represents the low range of the momentum flux ratio. The 18 round jets with a J_{OPT} of 103 represents the high range of the momentum flux ratio. A nine round jets module, 9RJ having a J_{OPT} equal to 25, representing the medium range of the momentum flux ratio. These three modules were designed such as J equals J_{OPT} when the mass flow rate through the jets is equal to the mass flow rate of the cross-flow. This design procedure couples the momentum flux ratio to the equivalence ratio. For each jet configuration, the actual momentum flux ratio at which the experiments were run was varied by varying the secondary air mass flow rate. The primary mass flow rate was kept constant. The secondary mass flow rate m_J was varied from 1.17 g/s to 5.44 g/s. Consequently the overall equivalence ratio varied from 0.5 to 1.1. The water-cooled probe was used to extract and freeze the sample. Before reaching the gas analyzer, the sample flows through a cooler which extracts the water contained in the sample.

3.3.2. Decoupling the Equivalence Ratio and the Momentum Flux Ratio

A series of nine round jets modules with different jet diameters were tested to decouple the effect of the equivalence ratio from the effect of the momentum flux ratio on combustion efficiency. Seven nine round jets modules were designed: 9RJ_a, 9RJ_b, 9RJ_c, 9RJ_d, 9RJ_e, 9RJ_f and 9RJ_g. All of those seven modules have the same optimum momentum flux ratio J_{OPT} (as predicted by Eq. (2-8)) but different Φ when J equals J_{OPT} . Table 3-4 presents the characteristics of these modules. For each of the previous modules, the secondary mass flow rate was varied from 1.17 g/s to 5.44 g/s to investigate the effect of the equivalence ratio.

3.3.3. Effect of Mixing

The rate of mixing between air and cross-flow gas can have an important effect on combustion efficiency. The eighteen round jets module was used to evaluate the unmixedness of the flow at 1.5 diameters downstream of the plane of the injection of the jets. The molar fractions of CO and CO₂ were measured at 50 locations in the cross section of the cross-flow for each value of the momentum flux ratio at which the experiment was run. The fifty locations were randomly chosen. The secondary air mass flow rate was varied so as to change the equivalence ratio. For each value of the momentum flux ratio, the unmixedness based on total carbon concentration was evaluated.

9 RJ Module	Diameter jet (mm)	Equivalence Ratio at J=Jopt	J at Equivalence Ratio $\phi=0.8$
a	3.18	0.79	25
b	3.97	0.63	13
c	2.05	1.13	186
d	2.64	0.97	68
e	2.37	1.04	104
f	2.9	0.91	46
g	2.5	1.01	84

Table 3-4 Characteristics of the nine Round Jets Modules

3.3.4. Effect of the Reaction Rate

The effect of the reaction rate on combustion efficiency was investigated by comparing the combustion efficiency of carbon monoxide and hydrogen.

The decomposition of methane (CH_4) in the primary reactor, at an equivalence ratio of 1.5, generates besides carbon dioxide and water, a considerable amount of molecular hydrogen and carbon monoxide. These two fuels are burnt in the mixing module. The chemical kinetics of these two fuels is very different. Table 3-5 provides comparative information extracted from Glassman (1987). Hydrogen flames are generally more stable than carbon monoxide flames. Hydrogen has a larger flammability limit than carbon monoxide. The flame speed for hydrogen is one order of magnitude higher than the flame speed for carbon monoxide. The hydrogen combustion efficiency is evaluated by measuring H_2 concentration in the exhaust.

3.3.5. Boundary Conditions Upstream of the Jets and Uniformity at 48 Diameters Downstream

The results presented in the literature review section were found for the case of a uniform cross-flow upstream of the plane of the injection of the jets. Moreover the concentrations of carbon monoxide and hydrogen are needed to normalize the actual concentration of carbon monoxide and hydrogen measured in the exhaust. For these reasons, the characterization of the flow upstream was carried out. The water-cooled probe was used to measure the concentrations of CO and CO_2 at one diameter upstream of the jets. The infrared detector was used for this purpose. These measurements were

made at 10 random positions in the cross-section. Three samples were also extracted and analyzed in the gas chromatograph to measure the concentration of hydrogen.

The measurements at 48 diameters downstream were made at one position in the cross-section assuming that at that cross-section the flow is fully mixed. To verify this assumption, a measurement of the unmixedness, based on total carbon concentration, at 48 diameters downstream was carried out for the 9RJd module. Carbon monoxide and carbon dioxide concentrations were measured at 12 positions in the cross-section. The unmixedness was evaluated for two secondary mass flows: 1.17 g/s and 5.44 g/s.

3.4. Error Analysis

The calculation of the residence time of the secondary air in the plenum and the exhaust gas in the tube sampler were made. The results of the calculation are in the appendices 1.

3.4.1. Carbon Monoxide Measurements

The specification sheet of the Nova 362WP analyzer gives an accuracy of 10 ppm for CO measurements. The drift is 1 % of the full scale over 8 hours. The experiments were run for less than 6 hours per experiment. Therefore the error due to the drift is less than $0.01 \cdot 20000 = 200 \text{ ppm} = .02\%$ for the high scale (measurement higher than 2000ppm) and less than $0.01 \cdot 2000 = 20 \text{ ppm}$ for the low range (measurements lower than 2000ppm). The measurement indicated by the analyzer fluctuates over time due the fluctuation of the actual concentration in the exhaust which arises from the instabilities of combustion. This fluctuation is estimated at $\pm 50 \text{ ppm}$. The total error on the measurements is $\pm 70 \text{ ppm}$ for the low range and $\pm 0.02\%$ for the high range.

	Laminar flame speed range (cm/s)	Stoichiometric fuel-air mixture (volume percent)	Lower flammability limit fuel-air mixture (volume percent)	Upper flammability limit fuel-air mixture (volume percent)
Hydrogen	200-300	29.2	4	75
Carbon monoxide	20-40	29.5	12.5	74.2

Table 3-5 Flammability Characteristics for CO and H₂

For each measurement point the experiment was run at least three times. For each value of J (or ϕ), there are thus at least three values of $[CO]$: $[CO]_1$, $[CO]_2$, and $[CO]_3$. The average and the experimental error are given, respectively, by the following two formulas:

$$[CO] = ([CO]_1 + [CO]_2 + [CO]_3) / 3 \quad (3-9)$$

$$\text{Error} = \text{Max}(|[CO] - [CO]_1|, |[CO] - [CO]_2|, |[CO] - [CO]_3|) \quad (3-10)$$

The larger estimate of the error, either what is given by Eq. (3-10) or the specification sheet, is taken to be the experimental error.

3.4.2. Hydrogen Measurements

For each of the samples extracted, three measurements of hydrogen concentration were made; and the error and the average were calculated using formulas similar to Eq. (3-9) and Eq. (3-10).

3.5. Summary

The objectives of the experiments designed are to test the effect on combustion efficiency of:

1. the equivalence ratio;
2. chemical kinetics;
3. the momentum flux ratio; and
4. mixing.

An estimate of the error on the measurements of CO and H₂ concentrations was made using a combination of the indications of the specification sheet of the analyzer used and the analysis of the experimental data.

The assumption of uniform concentration profile across the cross section of the cross-flow was checked as well as the assumption of full mixing at 48 diameters downstream.

4. Results and Discussion

The data collected during the experiments is presented in graphs and tables to support the discussion of the conclusions. The data that is used to plot the graphs is grouped in tables is given in the appendices 1 to 5. The chapter is structured into six different sections according to the main points discussed:

- The results of the concentration measurements of CO, CO₂, H₂ and CH₄ concentrations at inlet plane of the mixing module along with the results of the verification of the uniformity of the profile upstream of the jets and complete mixing at 48 diameters downstream;
- the discussion of the effect on the combustion efficiency of the equivalence ratio Φ ;
- the effect of the momentum flux ratio on the combustion efficiency;
- the influence of the number of jets;
- the effect of mixing; and
- the effect chemical kinetics.

The main conclusions of this investigation are summarized in the last paragraph.

4.1. Boundary Conditions

Besides checking the boundary conditions in the cross-flow upstream of the jets and the uniformity at 48 diameters downstream, that are discussed in the next two sections, the temperature in the plenum was measured. Appendices 1 represents these measurements at 2 mm and 2 cm from the plane of the injection of the jets into the cross-

flow. The measurements were done for the 9RJd module. They show that the difference is not significant. Therefore taking the measurements at 2 cm gives a good estimate of the temperature of the jets. The temperature of the jets was taken at 2 cm for all the experiments.

4.1.1. Boundary Conditions at the Entrance of the Mixing Module

To evaluate the combustion efficiency of hydrogen and carbon monoxide, it is essential to measure the actual concentration of these two species in the cross-flow entering the mixing module. Methane and air were burnt in the primary reactor at an equivalence ratio $\Phi=1.5$ to produce a flow of hot gases rich in carbon monoxide and hydrogen. Three samples were taken at one diameter upstream of the plane of the jets to check that all methane has reacted. The three samples were analyzed in a gas chromatograph. The methane concentration was found to be equal to 0.07 %, which means that essentially all of the methane has been consumed in the primary reactor. The gas chromatograph also provided the concentration of H_2 in the cross-flow at the entrance of the mixing module. The cross-flow contains 7.2 % and 5.8 % of hydrogen and carbon monoxide, respectively. Table 4-1 shows the concentrations of CO , CO_2 , CH_4 and H_2 at the entrance of the mixing module.

The theories and the experimental results discussed in the literature are for cross-flows displaying uniform concentration and velocity profiles upstream of the jets. To ensure the uniformity of the velocity profile, the hot gases coming from the reactor flow through a ceramic plug before entering the secondary module. This doesn't only ensure a uniform velocity but also allows a uniform distribution of the species and temperature

across the duct cross-section. To test that the cross-flow entering the mixing module displays a uniform profile, the unmixedness, based on the total carbon concentration, is evaluated at one diameter upstream of the plane of the jets. Carbon monoxide and carbon dioxide concentrations were measured at 11 random locations across the cross-section of the cross-flow. The average total carbon concentration is equal to 13 %. The unmixedness was evaluated as the ratio of the standard deviation of total carbon concentration over the average. It is equal to 2 % (Table 4-1). This unmixedness suggests that the condition of uniform profile upstream of the jets is satisfactorily achieved by the experimental setup.

4.1.2. Unmixedness at 48 Diameters Downstream

The measurements at 48 diameters downstream were done at the center of the cross section. This procedure assumes that the flow is completely mixed at that position. To check the validity of this assumption, the unmixedness based on the total carbon concentration (defined in section 3.2.3. of chapter 3) was evaluated at 48 diameters downstream. This was done for the 9RJd module. As discussed in section 4.5. of this chapter, mixing at 1.5 diameters downstream is a function of the momentum flux ratio. It displays an optimum around the secondary air mass flow rate equal to 1.55 g/s. Therefore the unmixedness was measured at 48 diameters downstream for two values of the secondary air mass flow rate: 3.11 g/s, closer to the optimum mixing, and 5.44 g/s where the unmixedness at 1.5 diameters downstream was found to be high.

	CO	CO ₂	H ₂	CH ₄	Total Carbon
Average %	5.81	7.25	7.20	0.07	13.05
Standard deviation %	0.06	0.21	0.20	0.01	0.28
Standard Deviation/ Average	0.01	0.03	0.03	0.14	0.02

Table 4-1 Boundary Conditions

The concentrations of carbon monoxide and carbon dioxide were measured at 15 random locations in the across the cross section. For both values of the secondary mass flow rate the unmixedness was smaller than 0.03, which means that the difference in the value of the total carbon concentration between different positions across the cross section is smaller than 3 % of the value of this concentration. Therefore the concentrations of carbon monoxide, carbon dioxide and hydrogen at the center of the cross section are representative of the average concentrations across the cross section at 48 diameters downstream of the plane of the injection of the jets.

Appendices 1 contains the data obtained from the experiments carried out to check the boundary conditions upstream of the jets and the assumption of complete mixing at 48 diameters downstream.

4.2. Effect of the Equivalence Ratio on CO Levels

Figure 4-1 presents the results of the measurement of the carbon monoxide concentration at 48 diameters downstream for the three modules 4RJ, 9RJ and 18RJ having 4, 9 and 18 jets, respectively. On the vertical axis we have the carbon concentration $[CO]$ normalized by the diluted concentration of carbon monoxide $[CO]_D$. On the horizontal axis we have the overall equivalence ratio. All of the three modules display a minimum CO concentration. The minimum occurs for all of the three modules at an equivalence ratio around 0.8. On one hand, for lean equivalence ratios (lower than 0.8), carbon monoxide concentration increases with decreasing Φ . On the other hand, for rich equivalence ratios (higher than 0.8), carbon monoxide concentration increases with increasing Φ . The concentrations measured for the 18 round jets module are consistently

lower than the concentrations measured for the 9 round jets modules, which, are at their turn, lower than the concentrations observed for the 4 round jets configuration.

Although there is no separate premixing stage between air (jets) and fuel (cross-flow containing CO and H₂) before being put together in the reacting environment, the figure shows that the combustion efficiency is strongly dependent on the equivalence ratio. Since the equivalence ratio has no effect on combustion efficiency in non-premixed systems, this strong dependence on Φ observed in this investigation suggests that there is some premixing occurring before the chemical reaction takes place.

Both chemical reaction and mixing require a finite time to occur. When the mixing time scale is shorter than the chemical time scale, some partial premixing occurs before combustion takes place. The dependence of combustion efficiency on the equivalence ratio suggests that the flow under investigation is in the partially premixed regime.

During the experiments that produced the data presented in Fig. (4-1), the equivalence ratio was coupled to the momentum flux ratio. The variation of the equivalence ratio was achieved by varying the secondary mass flow rate. Therefore the momentum flux ratio was varying along with the equivalence ratio. Moreover the three modules 4RJ, 9RJ and 18RJ were designed such as the optimum momentum flux ratio is equal to their respective optimum momentum flux ratio predicted by Eq. (2-8) when the secondary mass flow rate is equal to the cross-flow mass flow rate. This adds an additional coupling between the equivalence ratio and the optimum momentum flux ratio.

Figure 4-1 Carbon Monoxide Destruction Efficiency

A series of seven nine round jets modules were used to decouple the equivalence ratio from the momentum flux ratio. Figure 4-2 illustrates the combustion efficiency of the series of Modules 9RJ_a, 9RJ_b, 9RJ_c, 9RJ_d, 9RJ_e, 9RJ_f, and 9RJ_g. All of these seven modules have nine round jets but different jet diameters. Therefore they all have the same optimum momentum flux ratio J_{OPT} , according to Eq. (2-8), but different equivalence ratios when the momentum flux ratio is equal to J_{OPT} . For each of the seven modules, the concentration of carbon monoxide displays a minimum for a value of the momentum flux ratio that is different for each of the modules. This value of the momentum flux ratio J yielding minimum carbon concentration doesn't coincide with J_{OPT} predicted by Eq. (2-8) ($J_{OPT}= 26$ for 9 round jets) for all the modules except for the 9RJ_a module. The optimum combustion efficiency for these modules are displayed at momentum flux ratios spanning from $J=10$ to $J=160$. Thus the optimum flow conditions yielding the lowest emissions are not dictated by the momentum flux ratio J . Figure 4-3 shows the emissions of the same seven modules versus the equivalence ratio Φ . For all the 9 round jets modules presented in the figure, the lowest CO emissions happen at an equivalence ratio around 0.8. Thus Φ is the controlling parameter affecting the flow conditions yielding minimum emissions.

At a given equivalence ratio Φ , each of the seven modules has a different momentum flux ratio J and a different concentration of carbon monoxide in the exhaust. Although the momentum flux ratio does not control the optimum flow conditions, it does control the level of emissions at the optimum point. Figure (4-4) shows the concentration of CO for each of the seven nine round jets modules at Φ equal to 0.8 (around the minimum carbon monoxide emissions). On the vertical axis we have the normalized CO concentration at $\Phi=0.8$. On the horizontal axis we have the corresponding momentum

flux ratio J at $\Phi=0.8$ for each of the modules. The figure displays a sharp decrease of the emissions as J increases, for values of J smaller than J_{OPT} . For values of J larger than J_{OPT} , the curve is practically flat, displaying a slight increase. Similar to the non-reacting cross-flows the momentum flux ratio is the driving factor affecting mixing in the reacting cross-flow (as it will be discussed in section 4.5.). For values of J smaller than J_{OPT} , the jets under penetrate decreasing mixing. Poor mixing of CO and O₂ results in high levels of CO in the exhaust. For higher values of J (larger than J_{OPT}), although mixing is not optimal it is improved by the effect of the back flow. This would explain the slower rise of CO concentration for high values of J (higher than 26) compared to low values of J (lower than 26).

Several references in the literature state that flows similar to the flow investigated here are situated in the distributed reaction regime (partially premixed regime). Zelina and Ballal (1997) showed that emissions of CO from gas turbines (where an extensive use of air jets is present) is a function of the equivalence ratio. They observed that the results of their model as well as the results of measurements on a real gas turbine show a minimum CO emissions around $\Phi=0.6$. Rizk and Mongia (1993) also studied CO emissions from a gas turbine combustor. They reported that CO emissions are minimized around Φ equal to 0.7. The results of their model agreed with measurements done on a real gas turbine combustor.

Figure 4-2 Nine Round Jets Modules, Effect of J

Figure 4-3 Nine Round Jets Modules, Effect of Φ

Figure 4-4 Efficiency of the 9 Round Jets Modules at $\Phi=0.81$

More recently, a computational fluid dynamics study of this experiment, for the particular case of the four round jets, showed that the flow is indeed in the partially premixed regime (Urson 1999). The author used the laminar flamelet model to predict the chemical time scale and the $k-\epsilon$ turbulence model to evaluate the turbulence (mixing) time scale. It was found that the Damkohler number (the ratio of the chemical time scale over the turbulence time scale) was smaller than one, which situates the flow in the distributed reaction zone regime, where a certain amount of premixing occurs before combustion.

Appendices 2 contains the experimental data collected for the seven modules 9RJ_a, 9RJ_b, 9RJ_c, 9RJ_d, 9RJ_e, 9RJ_f, and 9RJ_g.

4.3. Effect of the Momentum Flux Ratio on the Destruction Efficiency of CO

The momentum flux ratio affects the level of emissions as shown by Fig. (4-3) and (4-4). In non-reacting flows, the momentum flux ratio is the most important controlling parameter affecting mixing. In contrast it doesn't have the expected effect on combustion efficiency. This is due to the system under study being in the partially premixed regime where mixing is faster than chemical reaction; thus partial premixing occurs before the reaction gets to take place.

The momentum flux ratio affects combustion efficiency by inducing a quenching effect since J was varied throughout the experiments by varying the jets mass flow rate. According to Zelina and Ballal (1997), carbon monoxide concentration increases when Φ

decreases below the optimum point ($\Phi=0.6$) due to cold air quenching and too low temperatures in the combustion zone.

Appendices 3 contain the experimental data for the 4RJ, 9RJ, and 18RJ modules.

4.4. Effect of the Number of Jets

Figure (4-1) shows that the minimum CO level for each module consistently decreases as the number of jets increases. Figure (4-5) shows the concentration of carbon monoxide at the optimum point as a function of the number of jets n . The three points represent the experimental values obtained for the four, nine and eighteen round jets modules, respectively. The curve represented in the figure is a trend line that shows the consistent decrease of carbon monoxide concentration as the number of jets increases. This is consistent with Holdeman (1993), who states that mixing in non-reacting flows improves as the design momentum flux ratio increases.

Figure (4-6) presents the same data as Fig. (4-1) but on a linear scale. It shows that the shape of the curve around the optimum Φ gets 'flatter' as the number of jets increases. This means that the level of emissions at the optimum point is more stable and is less affected by variations of the equivalence ratio around the optimum value for higher number of jets. This point is of practical interest in industry where processes are prone to variations that might affect the overall equivalence ratio of the system.

4.5. Effect of Mixing on Combustion Efficiency

Unmixedness calculations were based on the total carbon concentration. The concentrations of carbon monoxide and carbon dioxide were measured at 50 locations

across the cross section. The tests showed that a population of 50 points of measurement are statistically representative of the unmixedness across the cross section. Figure (4-7) shows that for a sample size of 50, the unmixedness across the cross section converges.

The unmixedness measurements were carried out to answer two questions:

- How does the combustion affect mixing (using Eq. (2-8) for non reacting flows as a baseline);
- How does mixing affect the combustion efficiency.

Figure (4-8) presents the results of the measurement of the unmixedness at 3 radii downstream of the plane of the injection of the jets for the 18 round jets module. On the vertical axis is presented the unmixedness based on total carbon concentration. Similar to mixing in non-reacting cross-flows, the unmixedness is affected by the momentum flux ratio. There is an optimum momentum flux ratio yielding the best mixing. However the best mixing does not occur at the optimum momentum flux ratio J_{OPT} predicted by Eq. (2-8) for non-reacting cross-flows. It occurs instead at J/J_{OPT} equal to about 0.3. It follows that the non-reacting flow correlation given by Eq. (2-8) does not seem accurate for reacting cross-flows.

Figure (4-9) shows the evolution of mixing as a function of the equivalence ratio. The best mixing occurs at an equivalence ratio around 1. Therefore mixing is not a driving factor that determines the flow conditions yielding the optimum combustion efficiency.

Appendices 4 contains the results of the unmixedness calculations for the 18J module.

Figure 4-5 Effect of the Number of Jets n

Figure 4-6 Carbon Monoxide Destruction Efficiency, Effect of n

Figure 4-7 Convergence of the Unmixedness (for $\Phi = 0.93$)

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Figure 4-8 Unmixedness Based on Total Carbon for Module 18RJ

4.6. Effect of the Reaction Rate on Combustion Efficiency

The role of the reaction rate is explored by comparing the destruction efficiencies of H_2 and CO. The two fuels have significantly different flame speeds, flammability limits and reaction rates. The results of the measurements of hydrogen concentration for the 4RJ and 18RJ modules are collected in Appendices 5.

Figure (4-10) shows that the combustion efficiency of hydrogen displays an optimum around an equivalence ratio equal to 0.8. The efficiency of the eighteen round jets module is consistently better than the efficiency of the 4 round jets module. Although having different chemical kinetic characteristics, hydrogen and carbon monoxide combustion efficiency display the same trends. Therefore chemical kinetics does not affect efficiency trends.

However chemical kinetics affects H_2 and CO levels in the exhaust. Figures (4-11) and (4-12) show that for both the four and the eighteen round jets modules the combustion efficiency of H_2 is consistently better than the combustion efficiency of CO. This is due to hydrogen having a faster rate of reaction, higher flame speeds (200 m/s for H_2 and 30 m/s for CO), and wider flammability limits (Glassman (1987)). For both the completely premixed and non-premixed systems hydrogen flames are less prone to extinction. For the premixed regime, the wider flammability limit of hydrogen yields a better combustion efficiency. In the case of the non premixed regime, it is the high reaction rate (lesser effect of the strain rate) that ensures a better combustion for hydrogen.

Figure 4-9 Unmixedness, and $[CO]/[CO]_D$ as a function of ϕ for Module 18RJ

Figure 4-10 Hydrogen Combustion Efficiency

Figure 4-11 Hydrogen and Carbon Monoxide Combustion Efficiency(4RJ)

Figure 4-12 Hydrogen and Carbon Monoxide Combustion Efficiency(18RJ)

4.7. Summary

The main aim of this study is to improve the understanding of the relationship between mixing, chemical kinetics, and combustion efficiency for air jets in a hot reacting cross-flow. The following are the key conclusions of this study:

1. The flow is situated in the partially premixed regime. Therefore the equivalence ratio is a driving parameter affecting the combustion efficiency;
2. The momentum flux ratio does not seem to have an effect on the flow conditions yielding optimum combustion efficiency. However it affects the level of emissions;
3. Non-reacting flow correlations predicting optimum mixing such as the correlation presented by Eq. (2-8) do not predict optimum mixing for reacting cross-flows;
4. Combustion efficiency improves with increasing the number of jets; and
5. Chemical kinetics doesn't affect the trends of the combustion efficiency, although it does affect the values of the concentration in the exhaust.

5. Conclusions

The outcome of the interaction between a set of air jets and a reacting cross-flow is the result of the interaction between mixing, reaction rate and heat release accompanying combustion. Each of these phenomena has a finite time in which it takes place. The relative order of magnitude of these time scales determines the regime of combustion in which the system is. The Damkohler number, Da , defined as the ratio of the mixing time scale and the chemical time scale, is used to predict the regime of combustion. The air jets are introduced into the reaction zone without prior premixing with the fuel (H_2 and CO contained in the cross-flow). Although the system is initially non-premixed, its combustion efficiency was found to display a strong dependence on the equivalence ratio. This shows that mixing is much faster than the chemical reaction (Small Da number) allowing some premixing to occur. Therefore the interaction between the jets and the reacting cross-flow occurs in the partially premixed regime.

Similar to the non-reacting cross-flows the momentum flux ratio has an important effect on mixing in the reacting cross-flow. There is an optimum momentum flux ratio at which the mixing is the best. The correlation of Holdeman (Eq. (2-8)) does not seem to predict the momentum flux ratio yielding optimum mixing for the reacting cross-flow, in the case of the eighteen round jets. This correlation was initially derived for non-reacting cross-flow, therefore not taking into account the effect of heat release on the density gradient. It is also a correlation derived for a range of momentum flux ratios smaller than 100; the J_{OPT} of the eighteen round jets is 104. Although the momentum flux ratio is not the driving factor setting the flow conditions yielding optimum combustion

efficiency, it has an important effect on the levels of emissions at the optimum point. It was found that emissions display a sharp decrease as the momentum flux ratio increased towards the value yielding optimum mixing. For values of the momentum flux ratio higher than the momentum flux ratio yielding optimum mixing, the emissions remain low and practically constant.

The number of jets affects the levels of emissions too. The higher the number of jets the lower the emissions. This is consistent with the results found in the literature on non-reacting cross-flows which state that mixing improves as the number of jets increases.

The comparison of the combustion efficiency of hydrogen and carbon monoxide has shown that the reaction rate does not affect the flow conditions yielding optimum combustion efficiency. The reaction rate does affect instead the level of emissions. It was found that the higher the reaction rate the lower are the emissions.

6. Recommendations for future work

The effect of the number of jets, the equivalence ratio and the momentum flux ratio on combustion efficiency was investigated. Many references in the literature suggest that the diameter of the jets does not affect either mixing nor combustion efficiency. The design of the modules tested was done assuming that the diameter of the jets is not affecting combustion. Recent references in the literature on non-reacting cross-flows (Blomeyer et al. (1999)) suggest that the diameter can affect mixing. As an extension to the investigation of the parameters affecting combustion efficiency, the effect of the jets diameter can be explored.

Equation (2-8) was used as a baseline throughout this study. This equation was established for the range 0-100 of the momentum flux ratio for the non-reacting cross-flow. Often during the experiments, the momentum flux ratio was higher than 100. Therefore it would be interesting to check the validity of Eq. (2-8) in predicting mixing in non-reacting cross-flow conditions corresponding to the reacting experiments. In addition, mixing in the reacting case was measured for the eighteen round jets module only. The extension of the unmixedness to the four and the nine round jets modules would explore the trends measured for a larger range of the momentum flux ratio.

The use of a probe to extract the sample perturbs the flow and induces local mixing at the point of measurement. The size of the probe also puts a limit on the spatial definition than can be achieved. In addition the sample is extracted, transferred and then analyzed. To be representative, the measurements under these conditions suppose a complete freezing of the interactions in the sample as soon as it is extracted, which is an assumption that might not be true. The use of an intrusive technique (thermocouples) in the measurement of the temperature limits the access to the point of measurement. The closer the probe gets to the point of measurement the more likely is to have a higher perturbation of the system. The use of non-intrusive techniques allows access to the points of measurement without perturbing the system. These technique offer also a good spatial resolution.

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Appendices

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Appendices 1

Initial Conditions and Unmixedness at 48 Diameters Downstream

Residence Times

Residence Time of the Secondary Air in the Plenum

	Volume (m ³)	Max flow rate (m ³ /s)	Min flow rate (m ³ /s)	Max residence time (s)	Min residence time (s)
short plenum	0.0008	0.0074	0.0016	0.51	0.11
long plenum	0.0020	0.0074	0.0016	1.24	0.27

Residence time in the Tube Sampler used for Hydrogen Measurements

Volume tube (m ³)	Flow rate (m ³ /s)	Residence time (s)
0.00025	0.000020	12.58

Temperature Measurements (plenum for the 9RJd module)

Air mass flow rate(g/s)	Temperature at 2mm from inlet jets (C)	Temperature at 2cm from inlet jets (C)
1.55	210	198
2.33	159	142
3.11	163	185
3.89	160	200
4.66	144	193
5.44	137	187

Boundary Conditions

Carbon Monoxide and Carbon Dioxide Measurements

x(mm)	y(mm)		CO %	CO ₂ %	Total C %	Average C	Stdev C	stdv/aver
-0.4	9.2		5.78	7.27	13.04	13.04		
-7.8	7.0		5.78	7.16	12.93	12.99	0.08	0.01
1.3	8.6		5.78	7.27	13.04	13.01	0.06	0.00
-6.7	14.0		5.78	7.16	12.93	12.99	0.06	0.00
4.0	18.3		5.78	7.16	12.93	12.98	0.06	0.00
2.8	15.7		5.78	7.16	12.93	12.97	0.06	0.00
6.3	10.0		5.78	7.05	12.83	12.95	0.07	0.01
-4.1	14.2		5.88	7.48	13.36	13.00	0.16	0.01
9.8	9.3		5.97	7.81	13.78	13.09	0.30	0.02
-0.2	10.3		5.78	7.05	12.83	13.06	0.29	0.02
0.0	0.0		5.78	7.16	12.93	13.05	0.28	0.02
		Average	5.80	7.25	13.05			
		Standard Deviation	0.06	0.21	0.27

Cross-flow Cross Section

Hydrogen and Methane Measurements

[CO] %	[CO ₂] %		[H ₂] %	[CH ₄] %
5.90	6.80		7.21	0.073
6.00	7.00		7.41	0.066
5.90	6.70		7.01	0.063
		Average	7.21	0.067
		Standard Deviation	0.20	0.005

Unmixedness at 48 Diameters Downstream

Secondary Air: 3.11 g/s

x (mm)	y (mm)	[CO] (%)	[CO ₂] (%)	Total Carbon (%)
12	1	0.3	7.7	8
12	6	0.3	8.1	8.4
12	12	0.3	8.2	8.5
16	12	0.3	8.2	8.5
16	18	0.3	8.4	8.7
16	23	0.3	8.7	9
22	13	0.2	8.4	8.6
22	8	0.2	8.4	8.6
13	8	0.2	8.1	8.3
10	8	0.2	8.2	8.4
5	8	0.2	8.3	8.5
5	14	0.2	8.3	8.5
10	14	0.2	8.3	8.5
15	14	0.2	8.3	8.5
12	1	0.2	8.1	8.3
			Avrage=	8.5
			Stdv=	0.2
			stdv/Aver	0.03

Secondary Air: 5.44 g/s

x (mm)	y (mm)	[CO] (%)	[CO2] (%)	Total Carbon (%)
12	1	0.3	5.5	5.8
12	5	0.3	5.6	5.9
12	8	0.3	5.6	5.9
16	8	0.3	5.6	5.9
16	12	0.3	5.6	5.9
20	12	0.3	5.7	6
20	16	0.3	5.7	6
24	16	0.3	5.8	6.1
24	19	0.2	5.7	5.9
17	19	0.3	5.7	6
12	19	0.2	5.7	5.9
12	10	0.2	5.7	5.9
7	10	0.2	5.7	5.9
7	15	0.2	5.7	5.9
16	12	0.3	5.7	6
			Average=	5.9
			Stdv=	0.07
			stdv/Aver	0.01

Appendices 2

Effect of the Equivalence Ratio

Module 9RJ_a

Φ	J	$[\text{co}]/[\text{co}]_d$
0.55	91	0.493
0.58	80	0.272
0.61	70	0.175
0.64	58	0.090
0.67	49	0.048
0.71	36	0.022
0.76	29	0.006
0.81	23	0.003
0.86	18	0.006
0.89	16	0.010
0.93	12	0.033
0.97	11	0.031
1.00	7	0.081

Module 9RJb

Φ	J	$[\text{co}]/[\text{co}]_d$
1.00	4	0.297
0.93	6	0.238
0.86	7	0.219
0.81	9	0.196
0.76	11	0.192
0.71	14	0.207
0.67	17	0.220
0.65	19	0.226
0.64	21	0.242
0.62	23	0.257
0.61	24	0.263
0.58	28	0.296
0.55	32	0.339

Module 9RJc

Φ	J	$[\text{co}]/[\text{co}]_d$
0.55	50	0.157
0.58	86	0.064
0.61	104	0.030
0.64	145	0.016
0.67	162	0.016
0.71	221	0.021
0.76	255	0.029
0.81	279	0.033
0.86	293	0.039
0.89	325	0.043
0.93	346	0.049
0.97	404	0.063
1.00	458	0.091

Module 9RJd

Φ	J	$[\text{co}]/[\text{co}]_d$
0.55	16	0.051
0.58	26	0.011
0.61	37	0.005
0.64	55	0.007
0.67	71	0.015
0.71	88	0.022
0.76	113	0.035
0.81	121	0.043
0.86	136	0.054
0.89	147	0.064
0.93	157	0.082
0.97	189	0.097
1.00	207	0.145

Module 9RJe

Φ	J	$[\text{co}]/[\text{co}]_d$
0.55	24	0.032
0.58	39	0.005
0.61	58	0.001
0.64	81	0.005
0.67	96	0.016
0.71	137	0.033
0.76	172	0.060
0.81	188	0.092
0.86	206	0.124
0.89	227	0.137
0.93	240	0.171
0.97	291	0.214
1.00	315	0.291

Module 9RJf

Φ	J	$[\text{co}]/[\text{co}]_d$
0.55	12	0.088
0.58	19	0.021
0.61	30	0.009
0.64	41	0.013
0.67	52	0.018
0.71	66	0.039
0.76	84	0.053
0.81	89	0.084
0.86	100	0.094
0.89	107	0.104
0.93	117	0.122
0.97	135	0.177
1.00	152	0.219

Module 9RJg

Φ	J	$[\text{co}]/[\text{co}]_d$
0.55	20	0.056
0.58	34	0.010
0.61	48	0.003
0.64	68	0.006
0.67	86	0.016
0.71	111	0.037
0.76	136	0.064
0.81	150	0.098
0.86	164	0.138
0.89	179	0.153
0.93	190	0.196
0.97	230	0.218
1.00	246	0.349

Appendices 3

Effect of the Momentum Flux Ratio

Module 18 RJ

Φ	J	J Δ^-	J Δ^+	J/J _{OPT}	J/J _{OPT} Δ^-	J/J _{OPT} Δ^+	[co]/[co] _D	[co]/[co] _D Δ^-	[co]/[co] _D Δ^+
0.55	309	36	37	3.01	0.35	0.36	0.235	0.060	0.032
0.58	279	25	23	2.72	0.25	0.22	0.150	0.025	0.23
0.61	239	31	23	2.33	0.3	0.22	0.099	0.031	0.023
0.64	206	26	22	2.01	0.26	0.22	0.052	0.014	0.012
0.67	174	22	19	1.70	0.21	0.19	0.024	0.005	0.009
0.71	146	17	16	1.42	0.16	0.16	0.010	0.004	0.006
0.76	116	14	12	1.13	0.13	0.11	0.004	0.002	0.003
0.81	91	9	9	0.89	0.09	0.09	0.001	0.001	0.002
0.86	69	5	5	0.67	0.05	0.05	0.001	0.001	0.001
0.89	60	4	5	0.59	0.04	0.04	0.002	0.002	0.001
0.93	51	3	1	0.50	0.03	0.01	0.009	0.008	0.01
0.97	44	1	1	0.42	0.01	0.01	0.014	0.009	0.013
1.00	34	3	2	0.33	0.03	0.02	0.059	0.039	0.053
1.05	27	1	1	0.26	0.01	0.01	0.117	0.09	0.076
1.10	20	2	1	0.20	0.02	0.01	0.200	0.162	0.107

Module 9 RJa

Φ	J	J Δ^-	J Δ^+	J/J _{OPT}	J/J _{OPT} Δ^-	J/J _{OPT} Δ^+	[col]/[co] _b	[col]/[co] _b Δ^-	[col]/[co] _b Δ^+
0.55	91	4	3	3.56	0.17	0.12	0.493	0.031	0.034
0.58	80	3	2	3.12	0.13	0.07	0.272	0.023	0.015
0.61	70	3	2	2.74	0.12	0.09	0.175	0.002	0.002
0.64	58	1	1	2.25	0.03	0.04	0.090	0.013	0.017
0.67	49	0	1	1.93	0.02	0.02	0.048	0.008	0.016
0.71	36	4	5	1.40	0.16	0.20	0.022	0.007	0.009
0.76	29	3	5	1.12	0.10	0.19	0.006	0.005	0.007
0.81	23	2	3	0.89	0.06	0.11	0.003	0.002	0.003
0.86	18	1	1	0.68	0.03	0.06	0.006	0.002	0.003
0.89	16	0	0	0.63	0.00	0	0.010	0.000	0.000
0.93	12	1	-1	0.47	0.04	0.03	0.033	0.014	0.014
0.97	11	0	0	0.42	0.00	0.00	0.031	0.000	0.000
1.00	7	0	0	0.29	0.00	0.00	0.081	0.000	0.000

Module 4 R.J

Φ	J	J Δ^-	J Δ^+	J/J _{OPT}	J/J _{OPT} Δ^-	J/J _{OPT} Δ^+	[co]/[co] _D	[co]/[co] Δ^-	[co]/[co] Δ^+	[co]/[co] _D
0.55	19	1	1	3.70	0.24	0.26	0.728	0.053		0.046
0.58	17	1	1	3.31	0.27	0.15	0.565	0.008		0.008
0.61	14	1	1	2.83	0.17	0.18	0.378	0.029		0.022
0.64	12	1	1	2.32	0.15	0.13	0.253	0.031		0.035
0.67	9	1	1	1.87	0.21	0.13	0.122	0.015		0.021
0.71	8	0	1	1.50	0.09	0.14	0.076	0.031		0.019
0.76	6	1	1	1.10	0.20	0.24	0.013	0.007		0.012
0.81	5	1	1	0.89	0.12	0.16	0.011	0.004		0.002
0.86	3	0	0	0.67	0.08	0.08	0.026	0.004		0.005
0.89	3	0	0	0.61	0.00	0.00	0.032	0.000		0.000
0.93	2	0	0	0.47	0.05	0.03	0.077	0.026		0.024
0.97	2	0	0	0.40	0.00	0.00	0.078	0.000		0.000
1.00	2	0	0	0.31	0.00	0.00	0.120	0.000		0.000
1.05	1	0	0	0.25	0.00	0.00	0.192	0.000		0.000
1.10	1	0	0	0.20	0.00	0.00	0.238	0.000		0.000

Appendices 4

Unmixedness Measurement

Secondary flow rate SLPMA	J	ϕ	Average total carbon	Standard deviation total carbon	Unmixed ness	J/J_{OPT}
50	13	1.15	9.76	1.04	0.10	0.12
60	17	1.10	9.21	0.67	0.09	0.16
70	22	1.05	9.37	0.61	0.08	0.21
80	28	1.00	8.84	0.51	0.08	0.27
90	35	0.97	8.74	0.59	0.09	0.34
100	43	0.93	8.76	0.68	0.09	0.41
100	43	0.93	8.35	0.64	0.10	0.42
110	51	0.89	8.17	0.67	0.10	0.49
120	60	0.86	7.75	0.70	0.11	0.58
150	92	0.78	7.67	1.02	0.13	0.88
240	213	0.61	6.04	1.05	0.17	2.05

Appendices 5

Effect of the Reaction Rate

Module 18 RJ

Φ	$[H_2]$	$[H_2]_D$	J/J_{OPT}	$[H_2]/[H_2]_D$	$[H_2]/[H_2]_D$ Δ^-	$[H_2]/[H_2]_D$ Δ^+
1.10	0.70	5.40	0.19	0.129	0.005	0.006
0.97	0.11	4.80	0.40	0.023	0.002	0.001
0.88	0.01	4.32	0.67	0.003	0.000	0.000
0.81	0.01	4.05	0.85	0.002	0.000	0.000
0.71	0.02	3.60	1.34	0.005	0.000	0.000
0.67	0.02	3.41	1.60	0.006	0.000	0.001
0.61	0.06	3.09	2.19	0.020	0.001	0.001
0.55	0.14	2.82	2.88	0.051	0.001	0.001
0.53	0.20	2.70	3.26	0.073	0.004	0.004

Module 4 RJ

Φ	$[\text{H}_2]$	$[\text{H}_2]_0$	J/J_{OPT}	$[\text{H}_2]/[\text{H}_2]_0$	$[\text{H}_2]/[\text{H}_2]_0$ Δ^-	$[\text{H}_2]/[\text{H}_2]_0$ Δ^+
1.10	0.91	5.40	0.20	0.17	0.01	0.00
0.97	0.24	4.80	0.41	0.05	0.00	0.00
0.86	0.07	4.32	0.68	0.02	0.00	0.00
0.81	0.02	4.05	0.98	0.01	0.00	0.00
0.71	0.05	3.60	1.62	0.01	0.00	0.00
0.67	0.11	3.41	1.92	0.03	0.00	0.00
0.61	0.45	3.09	2.64	0.15	0.01	0.00
0.55	0.83	2.62	3.44	0.30	0.03	0.05