Evaluation criteria for a flameless combustor based on recirculation and mixing - A CFD approach

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A R T I C L E   I N F O

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A B S T R A C T

In the present work, the effect of combustor geometry and inlet air velocity on flameless critical parameters such as recirculation ratio and mixing is investigated. The main objective is to develop evaluation criteria for flameless combustors design based on these critical parameters. A simple lab scale combustor with central air jet arrangement is employed for the analysis. Three-dimensional computations were performed under non-reacting conditions using ANSYS Fluent. Reducing the air jet diameter to half its original value leads to a 100\% increase in the recirculation ratio, which promotes flameless operation. Moreover, it results in a slightly more than 200\% increase in turbulence intensity, which encourages hot products entrainment and accelerates mixing with incoming reactants. From another side, scaling down the combustor to half its original size results in 66\% reduction of recirculation ratio, which might suppress flameless operation. Besides, it accelerates incoming reactants mixing in the near burner region due to the increased jet spreading and decay rate. These results show the considerable influence of combustor geometry on recirculation ratio and mixing. Furthermore, the critical role of later parameters in the previously reported transition between conventional and flameless combustion modes for the present combustor is demonstrated. A threshold value of recirculation ratio, $m_{\text{rec}}/\left(m_\text{fue} + m_\text{inj}\right)$, is found critical for flameless operation and is noticed to increase with increasing excess air ratio. Therefore, the two parameters are linked together through a developed mathematical correlation. Finally, combustor geometry is represented through the dimensionless parameters; air jet to combustor diameter ratio, and combustor scaling factor. Recirculation ratio is linked to these parameters through additional correlations. Through these developed correlations, geometry aspects for flameless combustors can be preliminary identified and/or evaluated.

1. Introduction

Flameless combustion is a novel combustion mode in which the flame has no visible nor audible signature. It is based on recirculating a substantial portion of hot product gases (300\%) to be mixed with inlet fresh reactants prior to combustion [1]. Due to this considerable amount of hot recirculated product gases, reaction zones become more distributed and the combustion is ‘kinetically controlled’ rather than ‘mixing controlled’. Flameless combustion has several attractive features such as a nearly uniform temperature distribution, ultra-low emissions levels, reduced noise, and high stability [2–4]. Recirculation ratio, $K = m_{\text{rec}}/(m_\text{fue} + m_\text{inj})$, is defined as the ratio between the recirculated product gases mass flowrate, $m_{\text{rec}}$, and the inlet fresh reactants mass flowrate, $m_\text{fue} + m_\text{inj}$ [1]. It is believed that for flameless mode to be sustained, recirculation ratio shall not be lower than a threshold value of 3 regardless the combustion temperature [1]. In addition, recirculated product gases and inlet fresh reactants shall be properly mixed before combustion. Maintaining combustion at such highly vitiated conditions; substantial exhaust gas content, high preheat temperature, and good mixing is the key behind ultra-low NO\(_x\) and CO emissions [5–7].

Being critical parameters to flameless operation, considerable literature was devoted to understand how recirculation ratio and mixing could be affected by combustor different geometrical aspects and inlet conditions [8–15]. Arghode et al. [16] investigated the effect of inlet air jet diameter on recirculation ratio. Reduction in the combustor inlet diameter is believed to increase the recirculation ratio, which promote flameless combustion. Their work was supported by the correlation of Ricou and Spalding [17] and Han and Mungal [18]. Li et al. [19] investigated the effect of jet strength, combustor diameter, and combustor exit on mixing characteristics in a multiple premixed jets combustor. They concluded that increasing air mass flowrate promotes mixing.
which in turn results in a more distributed flame. Decreasing combustor diameter, for that particular arrangement, appears to promote a central recirculation zone that eventually results in improved mixing characteristics. Finally, decreasing combustor exit diameter is found to accelerate the local flow allowing less time for CO oxidation. Similar results were obtained by Duwig et al. [13] during their experimental and numerical work on a multi premixed jets flameless combustor. Air jet flow is typically found to dominate the combustor dynamics compared with fuel jets [16,19]. Despite these efforts, limited studies, due to authors’ knowledge, reported a quantified sensitivity analysis of recirculation ratio and mixing variation with different combustor geometrical aspects [20–22]. The authors believe that such an analysis is important to identify the most critical geometrical parameters that can be optimized for flameless combustion operation. Besides, preliminary design criteria can be deduced from this analysis to provide suitable ground for combustion optimization studies.

Therefore, the present work has two main objectives. First to conduct a sensitivity analysis to understand the effect of different combustor geometrical aspects and inlet conditions on recirculation ratio and mixing. Second, to develop criteria for flameless combustor preliminary design and optimization based on this analysis. A simple flameless combustor geometry with a central air jet and multiple methane jets arrangement is used in the analysis. The combustor was reported in the literature for its capability to operate at either conventional or flameless combustion modes [23–25]. Three-dimensional computations were performed under non-reacting conditions using ANSYS Fluent. The present paper is organized as follows. First, the numerical framework is presented. Second, proper validation of the numerical model is conducted by comparing the numerical results with the experimental data available from Refs. [23–25] to gain confidence in the results obtained. Third, effects of combustor inlet air jet diameter and combustor size on recirculation ratio and mixing characteristics are investigated under isothermal conditions. Finally, several expressions are developed to help guiding a preliminary combustor design and/or optimization for flameless combustion.

2. Numerical framework

2.1. Geometric model

Fig. 1 shows a schematic drawing of the combustor used in the present analysis. The same combustor was reported in the experimental work of Verissimo et al. [23–25]. It consists of three main sections; the flameless burner, the combustor section and the exhaust section. The flameless burner utilizes one central air jet (6 mm diameter), and 16 fuel injectors (2 mm diameter) (Fig. 1a). The 16 fuel injectors are arranged on a 30 mm diameter circle in the azimuthal direction. The combustion section is a quartz cylinder of 100 mm inner diameter and 340 mm length. It is well insulated using a 30 mm thick ceramic fiber blanket. Fig. 1a demonstrates the details of both the flameless burner and the combustor section geometry. The exhaust section is a steel tapered cylinder of initial diameter 100 mm, 15° slope, and 150 mm length (not shown in Fig. 1a). Combustion air is preheated to 400 °C using electric heater. Natural gas (pure methane), is utilized as fuel and is introduced at ambient temperature. Due to the symmetry in the combustor geometry, a 1/16th section is used for our numerical computations to reduce the computational cost (Fig. 1b).
models are tested; the realizable $k$ - epsilon model (RKE) of Shih et al. [27], and the Menter’s shear stress transport $k$ – $\omega$ model (SST- $k$ $\omega$) [28]. Standard wall function is employed for the RKE turbulence model with the grid being coarsened near the wall (the first cell is of $y^+ = 40$ to 60). For the SST- $k$ $\omega$, the whole boundary layer is resolved up to the wall with the grid near the wall being refined (the first cell is of $y^+ < 5$). As for solution methods, the finite volume discretization method and the steady state pressure based solver are used. PISO algorithm (Pressure Implicit with Splitting of Operator) is used for the solution of the pressure corrected continuity equation. Spatial discretization of pressure, momentum and species transport equations are performed using the second order upwind scheme. Two criteria for verifying numerical solution convergence are adopted. First, when the monitored residuals drop below $10^{-6}$ for all transport equations. Second, when monitored velocity and pressure at several selected points inside the domain reach steady state. ANSYS-Fluent 16, is used for all numerical computations [29]. Computations are run on a desktop computer with an Intel core i7 CPU, 3.2 GHz, 16 GB RAM.

As for the imposed boundary conditions, inlet mass flow rate is entrusted to both air and fuel inlets. Pressure outlet is adopted at the combustor exit. No-slip condition with zero heat flux is applied to all wall boundaries. Periodic boundary condition is applied at the azimuthal planes.

Fig. 2 demonstrates the computational grid constructed for the present analysis. As mentioned before, a one-sixteenth section of the complete combustor domain is used due to geometric symmetry. Four grid resolutions were tested for a grid independence solution; 317000, 585000, 1067000, and 2051000 cells. Predicted axial velocity and pressure profiles for the last three grids were almost identical. Therefore, the second grid (585000 cells) is used for the present analysis.

### 2.2. Numerical model

Reynolds averaged Navier - Stokes equations (RANS) are used in the present computations along with the non-reacting species transport equations. Density is calculated from the ideal gas law. Two turbulent

Table 1
Geometric aspects and operating conditions for investigated cases.

<table>
<thead>
<tr>
<th>Run</th>
<th>Inlet air jet diameter ($d_a$) [mm]</th>
<th>Excess air ratio (fl)</th>
<th>Inlet air mass flowrate ($m_{in}$) [kg/s]</th>
<th>Inlet air jet momentum ($N$) [N]</th>
<th>Inlet Reynolds Number ($R_e$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a, 1b, 1c</td>
<td>10, 7, 6</td>
<td>1.3</td>
<td>$4.4 \times 10^{-3}$</td>
<td>0.51, 0.96, 1.4</td>
<td>17810, 24526, 29618</td>
</tr>
<tr>
<td>2a, 2b, 2c</td>
<td>11, 8, 7</td>
<td>1.5</td>
<td>$5.1 \times 10^{-3}$</td>
<td>0.51, 0.96, 1.4</td>
<td>17810, 24526, 29618</td>
</tr>
<tr>
<td>3a, 3b, 3c</td>
<td>13, 9, 8</td>
<td>1.7</td>
<td>$5.8 \times 10^{-3}$</td>
<td>0.51, 0.96, 1.4</td>
<td>17810, 24526, 29618</td>
</tr>
<tr>
<td>4a, 4b, 4c</td>
<td>$200, 100, 50$ * $S_c = 2, 1, 0.5$</td>
<td>1.7</td>
<td>$5.8 \times 10^{-3}$</td>
<td>0.84</td>
<td>22880</td>
</tr>
</tbody>
</table>

### 2.2.1. Investigated cases

Fig. 3 demonstrates the combustion mode map obtained experimentally by Verissimo et al. [11] for the present combustor. In this map, A represents the area of flameless combustion, B represents the area of transition mode, C represents the area of lean combustion mode, and finally D represents the area where no combustion takes place.

It can be noticed from the map that the combustor successfully operates in the flameless regime at excess air ratio, $\lambda_{fl}$ below 1.3 for the tested range of air jet momentum. However, at higher excess air ratio levels, $\lambda_{fl} = 1.5$, and 1.7, a minimum threshold value of air jet momentum, $N = 0.9$, is needed to sustain the flameless mode. Finally, the combustor appears to be unable to operate in the flameless mode for excess air ratios above 1.7 regardless the air jet momentum implied. Increasing $\lambda_{fl}$ from 1.3 to 1.7 is believed to result in the departure from flameless combustion mode because of the increased oxygen content in the product gas [23]. The combustor associated flow physics were not investigated. A recirculation zone is induced by the central air jet inside the combustor. Its formation and strength are thought to be directly related to the air jet strength (inlet air velocity) and the combustor size.
In another work, Li et al. [30] reported that the combustor exit contraction has a considerable effect on the central recirculation zone leading to a change in emission characteristics. Based on these works, the following parameters were all checked by the authors for their effect on recirculation ratio and mixing: inlet air mass flowrate ($m_{a}$), air jet diameter ($d_{a}$), air preheat temperature ($T_{air\ in\ let}$), inlet fuel mass flowrate ($m_{f}$), fuel jet diameter ($d_{f}$), combustor size ($D_{c}$), and exhaust section contraction ratio ($C_{R}$). Exhaust section contraction ratio is defined as the ratio of the exhaust section final diameter to its initial diameter. Increasing inlet air mass flowrate is noticed to affect non-reacting combustor dynamics through increasing the air inlet velocity and turbulence intensity. However, with a constant air jet diameter, it has minimal effect on recirculation ratio. Inlet fuel mass flowrate, fuel jet diameter, and exhaust section contraction ratio seem to have minimal effect on non-reacting combustor dynamics that seem to be dominated only by the air jet. Air preheat temperature is important for flameless combustion. However, in non-reacting conditions, it is noticed to affect only the inlet air density that in turn will alter the inlet air velocity. Consequently, the effect of air preheat on non-reacting combustor dynamics will be very similar to the effect of the inlet air mass flowrate. Only the combustor air jet diameter ($d_{a}$) and the combustor size ($D_{c}$) were noticed to have a considerable effect on recirculation ratio and mixing. Therefore, we report here only the effect of these two key parameters.

Nine operating cases are selected and investigated to understand the change in flow physics that may lay behind the transition among the different modes of combustion. These selected cases are pinpointed on the map in Fig. 2 and detailed in Table 1. First, Air jet diameter ($d_{a}$) is progressively reduced from 10 to 6 mm, while maintaining constant excess air ratio ($\lambda$) of 1.3. A developed air jet to combustor diameter ratio ($\beta = \frac{d_{a}}{D_{c}}$), inlet Reynolds number, and air jet momentum (N) are found to be in the ranges ($0.1$–$0.06$), ($17810$–$29618$), ($0.51$–$1.4\ N$) respectively. After that, $\lambda$ is increased to $1.5$ and $1.7$. Air jet diameter is sized so that same ranges of inlet Reynolds number and air jet momentum are maintained. Finally, the effect of combustor size scaling is demonstrated through two cases. In the first case, combustor size ($D_{c}$), is doubled from $D_{c1} = 100$ mm to $D_{c1} = 200$. Then, in the second case, it is reduced from $D_{c2} = 100$ mm to $D_{c2} = 50$ mm, and $D_{c1,2}$ are the initial and final combustor diameters respectively. Consequently, a developed combustor scaling factor ($\frac{D_{c2}}{D_{c1}}$) is varied from $2$ to $0.5$. Excess air ratio is kept constant at $\lambda = 1.7$ during these two cases. The selection of non-dimensional parameters such as inlet Reynolds number ($Re$), excess air ratio ($\lambda$), the developed air jet to combustor diameter

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Run (1ii) taken from Ref. [31]</th>
<th>Run (3ii) taken from Ref. [11]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet air jet diameter ($d_{a}$) [mm]</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Inlet fuel jet diameter ($d_{f}$) [mm]</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Inlet air mass flowrate ($m_{a}$) [kg/s]</td>
<td>$4.4 \times 10^{-3}$</td>
<td>$4.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>Inlet fuel (air) mass flowrate ($m_{f}$) [kg/s]</td>
<td>$0.2 \times 10^{-3}$</td>
<td>$0.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>Inlet air/fuel temperature, ($T_{inlet}$) [$^\circ$C]</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

Fig. 4. Turbulent models assessment and numerical validation, experimental data are taken from Refs. [11,26,31].
ratio ($\beta = \frac{d_a}{D_c}$), and the combustor scaling factor ($S_C$) is principally to generalize the present analysis. Fuel mass flowrate ($m_f$) is kept constant at $0.2 \times 10^{-3}$ kg/s for all cases investigated.

3. Results and discussion

3.1. Validation of the numerical model

Before studying the effect of the combustor air jet diameter ($d_a$) or the combustor size ($D_c$) on recirculation ratio and mixing, it is important to validate the numerical model used in this work. Our numerical computations are compared with the experimental measurements of Oliveira [31], and Verissimo et al. [11,26]. Methane was replaced with air in both works. The geometrical aspects and operating conditions of both works are summarized in Table 2.

Fig. 4 demonstrates the radial and axial distributions of the normalized axial velocity ($U/U_{inlet}$). The radial distribution of ($U/U_{inlet}$) is predicted at eight combustor axial locations ($x/L$ = 0.022 to 0.44). Numerical predictions are obtained for two inlet air jet diameters ($d_a = 6, 10$ mm) using two turbulent models; the RKE model, and the SST-$k\omega$ model. Comparisons with experimental data are made where available. Turbulent models appear to have minimal effect on the axial velocity predictions at the two inlet diameters tested. Slight deviation between the two models is only noticed at $x/L = 0.092$ for $d_a = 6$ mm, and at $x/L = 0.16$ for $d_a = 10$ mm near the combustor center line. This slight deviation is attributed to the high turbulence and jet breakdown in this region. Moreover, SST-$k\omega$ model is found to require longer computational time than RKE till full convergence is reached. This is attributed to the additional cells in the near wall region, and the more iterations needed till convergence. Therefore, the RKE turbulent model is used with the standard wall function for the present study. Further analysis of Fig. 4 reveals a very good agreement between numerical predictions and experimental measurements for $d_a = 6$ mm. However, for $d_a = 10$ mm, the jet decay rate numerically predicted is noticed to be slightly lower than the experimentally observed near the combustor centerline. This discrepancy is noticed at the first five axial locations ($x/L = 0$ to 0.23). Further, downstream the combustor, numerical predictions are found to agree well with the experimental measurements. Looking at the radial distribution of the normalized axial velocity at these locations ($x/L = 0$ to 0.23), it can be noted that the numerical predictions are slightly lower than the experimental measurements. This goes in line with the slower jet decay numerically predicted at the combustor centerline. It is concluded that the rate of jet momentum diffusion numerically predicted is slightly slower than the experimentally observed. However, the numerical model appears to correctly predict the variation of the jet decay rate with the inlet diameter. This can be demonstrated at the axial locations where experimental measurements are available for both diameters (ex. $x/L = 0.16$ and $x/L = 0.3$). Consequently, the present numerical model can be used with confidence to study the effect of combustor geometry on flow characteristics.

![Fig. 5. Predicted flow stream lines (upper half) and mean velocity vectors (lower half) at the combustor symmetry plane for (a) $\beta = 0.11$, (b) $\beta = 0.08$, and (c) $\beta = 0.07$, $\lambda = 1.5$.](image)

![Fig. 6. Effect of air jet to combustor diameter ratio, $\beta$, on recirculation ratio, $K$, $\lambda = 1.5$.](image)
3.2. Effect of combustor air jet diameter, \( d_a \)

Fig. 5 shows the predicted flow streamlines (upper half) and the mean velocity vectors (lower half) at the combustor symmetry plane for \( \lambda = 1.5 \) and \( \beta = 0.11 \) to 0.07. Due to the high air jet momentum, a recirculation zone is generated and is noticed to occupy a considerable volume of the combustor. This recirculation zone is believed to be critical for flameless combustion as it recirculates hot product gases to the near burner region where mixing with fresh reactants takes place. Reducing the air jet diameter does not appear to have any effect on the location or the size of the recirculation zone. However, the mean velocity inside the recirculation zone is noticed to increase with the reduction of the air jet diameter. Maintaining inlet air mass flowrate at a constant value, the increase of the mean velocity inside the recirculation zone is attributed to the increased amount of the recirculated gases. Consequently, reduction of air jet diameter is believed to favor flameless operation in reacting conditions.

To confirm this conclusion, Fig. 6 shows the computed axial profiles of the recirculation ratio, \( K \) along the combustor centerline at different air jet diameters. As expected, reducing the air jet diameter is noticed to increase the recirculation ratio. Moreover, at \( \beta = 0.11 \) (Run 2a in Fig. 4), the computed recirculation ratio is found to be 2.8 which is below the threshold value of 3 necessary for flameless combustion [1]. This explains its location on the map in the ‘no combustion’ area, see Fig. 3. Decreasing \( \beta \) to lower values; 0.08, and 0.07, is found to increase the recirculation ratio, \( K \), to above 3 which favors flameless operation (run 2b, and 2c in the map of Fig. 3). Consequently, recirculation ratio can be considered as the main mechanism that lies behind the transition to flameless mode. Moreover, it can be used as an optimization parameter for flameless combustors preliminary design. To reach this objective, the variation of recirculation ratio, \( K \), with the combustor geometry; \( \beta \), is plotted in Fig. 7. Moreover, a mathematical expression is developed for this variation using curve fitting (eq. (1)):

\[
K = 0.1967 \beta^{-1.216}
\]

(1)

Where \( \beta = \frac{d_a}{D_c} \).

Fig. 8 shows the predicted radial profiles of the normalized axial velocity at different air jet diameters, \( \lambda = 1.5 \).

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0.07). The axial velocity is normalized by combustor inlet velocity. Reducing air jet diameter is noticed to accelerate the jet decay apparently because of the conserved jet momentum flux while moving downstream.

Fig. 9 shows the predicted contours of turbulence intensity at half the combustor symmetry plane for different air jet diameters. Turbulence intensity is believed to be a qualitative measure for the mixing intensity inside the combustor. Reducing the air jet diameter is noticed to result in a considerable increase in turbulence intensity especially in the shear layer between the air jet and the surrounding medium. This shear layer becomes more unstable and more prone to Kelvin-Helmholtz instabilities as jet velocity increases (i.e. jet diameter reduction). More vortical structures are generated and convected downstream resulting in an increased area of high turbulence intensity, see Fig. 9. Moreover, these vortical structures promote exhaust gases entrainment and mixing with the incoming reactants which eventually lead to a more distributed reaction.

Fig. 10 shows the axial distribution of CH₄ mass fraction along the combustor centerline. Reducing the air jet diameter results in an increase of the air jet velocity. Consequently, the air to fuel jets momentum ratio is increased which results in faster entrainment of the fuel in the air jet as seen from Fig. 10a. This faster entrainment of fuel into the air jet accelerates the air-fuel mixing process (see Fig. 10b) which may result in moving the reaction zone in the combustor upstream direction.

In previous computations (not included in this paper), the effect of inlet air mass flowrate, hence, excess air ratio, on recirculation zone location and size, jet decay, and recirculation ratio was studied and no apparent effect was noticed. Consequently, flow dynamics inside the combustor is dominated more likely by the change in the air jet diameter than by the change in air mass flowrate, i.e. excess air ratio. Increasing the latter is only found to result in increasing the oxygen content in the recirculated product gases, which subsequently lead to abortion from flameless operation.

Fig. 11. Predicted flow stream lines (upper half) and mean velocity vectors (lower half) at the combustor symmetry plane for (a) $S_C = 1$, and (b) $S_C = 0.5$ (zoomed), $\lambda = 1.5$.
3.3. Effect of combustor size, \( S_C \)

Combustor diameter is reduced from an initial value, \( D_{ci} = 100 \text{ mm} \) to a final value, \( D_{cf} = 50 \text{ mm} \). A developed scaling factor, \( S_C = \frac{D_{ci}}{D_{cf}} \), is reduced accordingly from 1 to 0.5. Fig. 11 shows the predicted flow streamlines (upper half) and the mean velocity vectors (lower half) at

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Fig. 14. Effect of combustor size (\( S_C = \frac{D_{ci}}{D_{cf}} \)) on the axial air jet decay along the combustor center line, \( \lambda = 1.5 \).

Fig. 15. Predicted contours of turbulence intensity at half the combustor symmetry plane for (a) \( S_C = 1 \), and (b) \( S_C = 0.5 \) (zoomed), \( \lambda = 1.5 \).

Fig. 16. Effect of combustor size (\( S_C = \frac{D_{ci}}{D_{cf}} \)) on (a) Fuel mass fraction, (b) Air-fuel mixing rate, along combustor center line, \( \lambda = 1.5 \).

Fig. 17. Computed values of \( K \) and \( \beta \) for different investigated cases.

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the combustor symmetry plane for $S_C = 1$, and 0.5. Excess air ratio is kept constant at $\lambda = 1.7$. Apparently, reducing the combustor size to half its original value results in reducing the recirculation zone size with nearly the same percentage. Consequently, the center of the recirculation zone is noticed to be shifted toward the upstream direction leading to a faster flow reattachment to the wall. Maintaining both the inlet mass flow rate and velocity constants, the recirculated mass is expected to decrease in proportion to the reduction in the recirculation zone size.

To confirm this conclusion, Fig. 12 shows the computed axial profiles of the recirculation ratio, $K$, along the combustor centerline for two combustor sizes. As expected, combustor size reduction by 50% leads to a reduction in the recirculation ratio by 66% and a shift of its peak toward the upstream direction. To further confirm this relation, combustor size is doubled from $S_C = 1$, to $S_C = 2$ (computations of this run are not included here). An increase in recirculation ratio by 300% is noticed following the duplication of the combustor size. Fig. 13 shows the computed variation of recirculation ratio, $K$, with the combustor size. An increase in recirculation ratio by 300% is noticed in Fig. 11 and faster jet decay. However, the high turbulence behavior can be attributed to the reduction in the recirculation zone size.

The following conclusions were reached:

1. Given excess air ratio, $\lambda$, the minimum recirculation ratio, $K_{\text{critical}}$, to achieve flameless combustion can be estimated from either eq. (2) or the curve plotted in Fig. 18.

$$K = 3.2716 S_C^{1.5905}$$  \hspace{1cm} (2)

2. Scaling down the combustor to half its original size results in 66% reduction of recirculation ratio, $K$, and combustor scaling factor, $S_C$, through the following two expressions:

$$K = 0.1967 \beta^{-1.216}$$  \hspace{1cm} (3)

$$K = 3.2716 S_C^{1.5905}$$

To help developing criteria for flameless combustor preliminary design and/or optimization, the recirculation ratio, $K$, is calculated for the different values of $\beta$ using the former expression (eq. (1)). Fig. 17 demonstrates both values of $\beta$, and $K$, for all runs investigated in the present work.

It is apparent that as the level of excess air increases inside the combustor, the minimum necessary value of recirculation ratio, $K_{\text{critical}}$, increases. This can be explained as increasing excess air results in increased levels of oxygen inside the combustor. These elevated oxygen levels necessitate more recirculated exhaust gases to help keeping the reactant mixture vitiated for flameless operation. Fig. 18 demonstrates the minimum value of recirculation ratio, $K_{\text{critical}}$, necessary for flameless combustion computed at different excess air ratios for the present combustor.

From the curve above, using curve fitting, the following expression is developed:

$$K_{\text{critical}} = -10.476 x^2 + 35.9 \lambda - 26.805$$  \hspace{1cm} (3)

Consequently, preliminary sizing criteria for the present arrangement; non-premixed combustors with central air jet, can be set as follows:

1. After $K_{\text{critical}}$ is calculated, maximum inlet air jet to combustor diameter ratio $\beta$, that can maintain flameless operation can be estimated from either eq. (3) or the curve plotted in Fig. 18.

2. Minimum combustor size, $S_C$, that can maintain flameless operation can be estimated from either eq. (2) or the curve plotted in Fig. 13.

However, further work will be done in the near future to include the effect of both inlet air preheat temperature and combustor thermal loading into this criteria. The final objective is to reach more complete and generalized formulations for the sizing of non-premixed flameless combustors with central air jet arrangement.

4. Conclusions

Numerical non-reacting computations aimed to study the effect of both combustor geometry and inlet air velocity on recirculation ratio and mixing were performed. Criteria for the preliminary design and optimization of the non-premixed flameless combustors with central air jet arrangement was then developed.

The following conclusions were reached:

1. Reducing the air jet diameter to half its original value results in a 100% increase in the recirculation ratio. This increase in recirculation ratio significantly promotes combustor operation in the flameless mode.

2. Scalling down the combustor to half its original size results in 66% reduction of recirculation ratio, which might cause abortion from the flameless mode.

3. As the level of excess air increases inside the combustor, the
minimum necessary value of recirculation ratio, $K_{\text{critical}}$, to achieve flameless combustion increases as well.

4. Several expressions are developed to help guiding a preliminary combustor design and/or optimization for flameless combustion.

Compliance with ethical standards

The authors declare that they have no conflict of interest.

Declarations of interest

None

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