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The influence of aspect ratio on the iso-thermal flow characteristics of multiple confined jets

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We report a systematic study of the interaction between four rotationally symmetric jets within a cylindrical chamber obtained with particle image velocimetry, under conditions relevant to a wide range of practical applications including the hybrid solar receiver combustor. The geometry consists of a cylindrical cavity with four inlet jets (representing four burners), which are configured in an annular arrangement and aligned at an inclination angle ($\alpha_j$) to the axis with a tangential component (azimuthal angle $\theta_j$) to generate a swirl in the chamber. The configurations of $\alpha_j = 25^\circ$ were assessed with two azimuthal angles $\theta_j = 5^\circ$ and $15^\circ$, a range of chamber aspect ratios ($L_c/D_c$), and a fixed nozzle Reynolds number of $Re_D = 10\,500$. The experimental results reveal a significant dependence of the mean and turbulent flow-fields on the aspect ratio $L_c/D_c$ for the values of $\alpha_j$ and $\theta_j$ considered here. Three different flow regimes and their controlling parameters were identified within the range $1 \leq L_c/D_c \leq 3$. The dependence of the flow characteristics on the chamber length $L_c$ was weak within $1.5 \leq L_c/D_c \leq 3$, but significant for $1 \leq L_c/D_c \leq 1.5$. It was also found that the value of $L_c/D_c$ has a controlling influence on the position and strength of large-scale recirculation regions, together with the extent of flow unsteadiness, although this influence is reduced as $\theta_j$ is increased. Published by AIP Publishing. https://doi.org/10.1063/1.5063500

I. INTRODUCTION

Multiple confined jets have been widely used in engineering applications such as solar receiver reactors,1 gas turbine engines,2 ventilation systems,3 and multiple-burner combustors.4 However, comprehensive understanding of the flow-field in these systems is still lacking owing to the large number of controlling parameters, such as jet angles,5 the extent of confinement by walls,6 and flow conditions.7 Of particular interest here are those configurations featuring multiple jets of relevance to the Hybrid Solar Receiver Combustor (HSRC) under development at the University of Adelaide.8-12 This device features a cavity that is operable as either a solar receiver or a combustion chamber equipped with multiple burners to direct fuel and air into the main cavity and tubular heat exchangers to transfer the thermal energy to the heat transfer fluid. The burners are configured in an annular ring and aligned at an inclination angle ($\alpha_j$) relative to the axis of the cavity and/or at an azimuthal angle ($\theta_j$) relative to the axis of the burner, resulting in a swirling flow within the main cavity. For conditions in which both $\alpha_j > 0^\circ$ and $\theta_j > 0^\circ$, this arrangement is termed “rotationally symmetric.” Previous investigations of the flow-fields within the HSRC revealed a significant effect of the jet angles ($\alpha_j$ and $\theta_j$) on the strength and position of the large-scale recirculation which is critical for achieving desirable flow regimes.10,11 In addition, the aspect ratio of $L_c/D_c$ has a strong influence on thermal efficiency and capital cost.9,12 Nevertheless, the dependence of the important flow characteristics on the key geometrical parameters, such as the length ($L_c$) and diameter ($D_c$) of the chamber, remains unknown. Hence, the overall objective of the present paper is to provide new understanding of the flow characteristics generated with multiple rotationally symmetric inlet-jets within a cylindrical chamber for a range of chamber aspect ratios $L_c/D_c$.

Previous studies of flow-fields generated with multiple symmetric jets within a confined space revealed that the flow structure depends strongly on the arrangement and geometrical features of jets.3,4,10,11,13-16 Chammen et al.3 defined the flow structure downstream from the jet impingement point ($P_i$) as the “resulting jet flow” and that upstream as the “upstream reverse flow” noting that these flow features are significantly influenced by $\alpha_j$. The experimental studies of Boushaki and Sautet4 employing Particle Image Velocimetry (PIV) showed that an increase in $\alpha_j$ from 0° to 30° leads to a significant increase in the magnitude of mean and turbulent velocity fields within the jet merging region. Similarly, the PIV measurements of Long et al.10,11 found a strong dependence on jet angles ($\alpha_j$ and $\theta_j$) of the instantaneous and mean flow-fields generated with multiple symmetric jets. However, to the best of our knowledge, little or no information is available for the key geometrical parameters (e.g., $L_c$ and $D_c$) of the confined space for multiple jet configurations, although the aspect ratio of geometry has been found to have a significant influence on the flow-fields of free jet impingement17-19 and cavity flow.20-22 Importantly, the existing experimental data provide insufficient information to...
adequately understand the effect of the aspect ratio on the multiple confined jets in which both $\alpha_j$ and $\theta_j$ are variables. Hence, there is a need to obtain reliable, comprehensive, and sufficient data to fully characterize the influence of the chamber aspect ratio $L_c/D_c$ on the mean and RMS (root-mean-square) flow-field generated with multiple inclined jets in a confined space.

The influence of confinement on the flow-fields has been investigated for a wide range of applications.\textsuperscript{16,17,23–27} It has been found that the distance between the jet exit and an end plate, termed “confinement height” ($H_c$), can significantly influence the position and strength of the recirculation regions, wall jet development, and jet velocity.\textsuperscript{17,23,24,26} It has also been found that the influence of the aspect ratio of a confined space is significant for near-field but negligible for far-field within a swirled jet chamber.\textsuperscript{27} However, while these previous studies provide useful insight, they are of limited value for model validation due to the lack of information available for the inflow and boundary conditions. Another limit of these studies is that they have been performed almost exclusively for a single jet, which makes it difficult to directly apply to multiple confined jets. In our previous work, Long et al.\textsuperscript{11} revealed the presence of both an external and internal recirculation zone (ERZ and CRZ) within these configurations. The ERZ and CRZ regions are associated with the entrainment rate (or the recirculation rate) within the chamber, which is important for combustion stabilization and thermal efficiency.\textsuperscript{28–30} However, this was assessed for a fixed value of $L_c/D_c = 3$ so that the influence of $L_c/D_c$ on large-scale recirculation regions is yet to be reported. Hence, additional measurements are needed to identify the influence of the chamber aspect ratio $L_c/D_c$ on the dominant recirculation zones generated by multiple jets within a cylindrical chamber.

To meet the aforementioned needs, the present paper aims to provide new understanding of the iso-thermal flow-fields generated with a Multiple Impinging Jet in a Cylindrical Chamber, termed “MIJCC.” More specifically, it aims: (a) to provide a detailed characterization of the flow generated with multiple rotationally symmetric inlet-jets within a cylindrical chamber for the aspect ratios $L_c/D_c = 3, 2.5, 2, 1.5,$ and $1$; (b) to identify the influence of the chamber aspect ratio $L_c/D_c$ on both the mean and RMS flow-fields within a cylindrical chamber with multiple jets; and (c) to characterize the dependence of the large-scale recirculation zones (ERZ and CRZ) on the aspect ratio $L_c/D_c$ for low-swirl ($\alpha_j = 25^\circ$ and $\theta_j = 5^\circ$) and high-swirl ($\alpha_j = 25^\circ$ and $\theta_j = 15^\circ$) jet configurations.

II. METHODOLOGY

A. Experimental configurations

The experimental MIJCC configuration is presented schematically in Fig. 1. The design principles have been reported in our previous work,\textsuperscript{11} so here only the key geometrical features are discussed. The cavity of the MIJCC consists of a cylindrical chamber with a conical expansion, a secondary concentrator (SC), and four rotationally symmetric inlet jets ($N_j = 4$). The inlet jets were distributed around the main cavity with a combination of an inclination angle ($\alpha_j$) and an azimuthal angle ($\theta_j$). The flow leaves the device through an annular outlet around a bluff end-wall.

The values of the key geometrical parameters are listed in Table I. The diameter of the MIJCC was fixed at $D_c = 74$ mm, while the length of the chamber was set at either $L_c = 185$ mm, 148 mm, $111$ mm, or 74 mm, resulting in aspect ratios of $L_c/D_c = 2.5, 2, 1.5,$ or $1$. These ratios were selected to span a sufficient range of flow-features and cover realistic geometrical dimensions for relevant applications. In addition, the chamber length of our previous work $L_c = 225$ mm ($L_c/D_c = 3$) was chosen as reference cases for comparison with the present study (labelled with an asterisk in Table II). Two azimuthal angles of $\theta_j = 5^\circ$ and $15^\circ$ were investigated at a fixed inclination angle of $\alpha_j = 25^\circ$, representing the “low-swirl” and “high-swirl” configurations, respectively. These angles were chosen to generate the two main classes of flow identified in our previous work,\textsuperscript{11} which found that either a dominant ERZ or CRZ regime can be generated within the cylindrical chamber, depending on the geometry. All experimental cases are listed in Table II.

FIG. 1. Schematic diagram of the MIJCC configurations investigated in the present study, showing the key geometrical parameters from the axial cross section (left) and the radial cross section (right).
### TABLE I. Values of the geometrical parameters of the MIJCC configurations investigated in the present study.

| Dimensions | Description | Value |
|------------|-------------|-------|
| $D_c$      | Chamber diameter (mm) | 74    |
| $D_{sc}$   | Diameter of the SC (mm) | 74    |
| $D_{th}$   | Throat diameter (mm) | 24.6  |
| $D_{pipe}$ | Inlet pipe diameter (mm) | 3.35  |
| $L_c$      | Chamber length (mm) | 185, 148, 111, and 74 |
| $L_{pipe}$ | Inlet pipe length (mm) | 150   |
| $W_{out}$  | Width of the outlet gap (mm) | 3     |
| $\beta_{con}$ | Conical expansion angle (deg) | 40    |
| $\gamma_{sc}$ | Angle of the SC (deg) | 40    |
| $\alpha_j$ | Jet inclination angle (deg) | 25    |
| $\theta_j$ | Jet azimuthal angle (deg) | 5 and 15 |

### TABLE II. The notation for the MIJCC configurations investigated in the present study.

| Experiment case no. | Configurations | Jet angles, $\alpha_j$ and $\theta_j$ (deg) | Chamber aspect ratio, $L_c/D_c$ |
|---------------------|----------------|------------------------------------------|-------------------------------|
| 1                   | MIJCC-05-LD25  | 25 and 5                                 | 2.5                           |
| 2                   | MIJCC-05-LD20  | 25 and 5                                 | 2                             |
| 3                   | MIJCC-05-LD15  | 25 and 5                                 | 1.5                           |
| 4                   | MIJCC-05-LD10  | 25 and 5                                 | 1                             |
| 5                   | MIJCC-15-LD25  | 25 and 15                                | 2.5                           |
| 6                   | MIJCC-15-LD20  | 25 and 15                                | 2                             |
| 7                   | MIJCC-15-LD15  | 25 and 15                                | 1.5                           |
| 8                   | MIJCC-15-LD10  | 25 and 15                                | 1                             |
| 9                   | MIJCC-05-LD30  | 25 and 5                                 | 3                             |
| 10                  | MIJCC-15-LD30  | 25 and 15                                | 3                             |

### B. Experimental arrangement

The present experimental arrangement is similar to that reported previously, so only the key experimental apparatus and parameters are described here. Planar Particle Image Velocimetry (PIV) was employed to investigate the mean and RMS flow-fields with the MIJCC configurations. The working fluid was water at ambient temperature, while a closed-loop system was used to recirculate the water from the outlets of the tank to the inlet-pipes. A symmetrical manifold system feeds fluid to four pipes with a length-to-diameter ratio of $L_{pipe}/D_{pipe} \approx 196$ (the straight pipe has a length of $46D_{pipe}$, and the gently curved flexible pipe has a length of $150D_{pipe}$), which ensures that a fully developed pipe flow is achieved at the pipe exit plane. The flow was seeded with hollow glass spheres with a specific gravity of 1.1 and a particle diameter of 12 µm.

The optical arrangement, together with the axial measurement region, is presented schematically in Fig. 2, while the details of the key experimental parameters are listed in Table III. A Nd:YAG laser (Quantel Brilliant B) was used to generate a light sheet with a combination of three cylindrical lenses (Thorlabs). A Charged Coupled Device (CCD) camera (Kodak Megaplus ES2093) was used to capture the PIV images for each measurement.

A total of 1900 PIV image pairs was collected and processed for each experimental condition. An in-house PIV code in MATLAB R2015a (Mathworks) was employed to process the raw images. A multi-grid correlation algorithm with 50% overlap was applied to calculate the displacement of seeding particles and also to minimize noise. Outliers (erroneous vectors) were identified by using an in-house PIV code in the post-processing, which compares the value difference between

![FIG. 2. (a) Schematic diagram of the PIV setup, showing the Nd:YAG laser, optical arrangement, water tank, and camera, (b) the axial measurement region (green box enclosed by a red dashed line) relative to the chamber (not to scale), and (c) the radial cross section, showing the laser sheet.]
TABLE III. Details of the key experimental parameters for the present PIV measurements.

| Experimental parameters                        | Value |
|------------------------------------------------|-------|
| Bulk mean velocity at the nozzle exit, $U_e$ (m/s) | 2.8   |
| Inlet Reynolds number, $Re_D$                   | 10500 |
| Laser wavelength (nm)                          | 532   |
| Laser thickness (mm)                           | 1.5   |
| Camera array size (pixels)                     | 1920×1080 |
| Measurement region (mm)                        | 123×65 |
| Image bit depth (bit)                          | 12    |
| Spatial resolution (mm)                        | 2     |
| Interrogation window (pixels)                  | $32×32$ |

The overall uncertainty ($\epsilon_{\text{overall}}$) associated with the PIV measurements was assessed via a series of systematic analyses, which accounted for the uncertainty derived from the experimental apparatus (2%), calibration ($\pm 0.05$ mm), laser time-delay (2%), and the image sample size (1%). On these bases, the overall uncertainty for the present PIV measurements was calculated to be $\epsilon_{\text{overall}} \approx 5\%$.

III. RESULTS AND DISCUSSION

A. Mean flow fields

Figure 3 presents the contours of the mean axial velocity ($U_x$) normalized by the nozzle exit velocity ($U_e$), showing the streamlines, labelled with arrows to indicate the flow direction (white arrows), and magnitude (color map) for the configuration of $\alpha_j = 25^\circ$ and $\theta_j = 5^\circ$ with (a) $L_c/D_c = 2.5$, (b) $L_c/D_c = 2$, (c) $L_c/D_c = 1.5$, and (d) $L_c/D_c = 1$ and for

FIG. 3. Mean axial velocity normalized by the nozzle exit velocity ($U_x/U_e$), showing the streamlines, labelled with arrows to indicate the flow direction (white arrows), and magnitude (color map), for the configuration of $\alpha_j = 25^\circ$ with $\theta_j = 5^\circ$ and $15^\circ$ for (a) and (e) $L_c/D_c = 2.5$, (b) and (f) $L_c/D_c = 2$, (c) and (g) $L_c/D_c = 1.5$, and (d) and (h) $L_c/D_c = 1$. Here $x$ and $r$ denote the axial and radial locations of the chamber, respectively. The orange dashed line denotes the upstream end of the annular outlet, while the region downstream from this line refers to the exit plane.
the configuration of $\alpha_j = 25^\circ$ and $\theta_j = 15^\circ$ with (e) $L_c/D_c = 2.5$, (f) $L_r/D_r = 2$, (g) $L_c/D_c = 1.5$, and (h) $L_r/D_r = 1$. Here $x$ and $r$ denote the axial and radial locations of the chamber, respectively. The orange dashed line denotes the upstream end of the annular outlet, while the region downstream from this line refers to the exit plane. The location of the vortex-core was determined by a combination of mathematical calculations described by Grosjean et al. and visual observation. Owing to the symmetry of the flow in the MJCC configurations, which was reconfirmed in the preliminary measurements, only half of the measured region is presented here. For the configurations where $\theta_j = 5^\circ$ [Figs. 3(a)–3(d)], it can be seen that a central resulting jet flow occurs for all cases downstream from the merging point ($P_{mer}$) of the four inlet jets. This resulting flow generates a large vortex (counter-clockwise in Fig. 3), with the vortex-core marked with a white “×” dubbed the external recirculation zone (ERZ). The secondary vortex that was found in the previous work of $L_r/D_r = 3$, if present, must be outside of the imaged region for $L_r/D_r = 2.5$.

It can be seen that the position of the ERZ is almost independent of the chamber length for $L_r/D_r \geq 2$. For example, the axial location of the ERZ vortex-core relative to the throat location, $x_{core}$, remains constant at $x_{core} \approx 80$ mm as $L_r/D_r$ is reduced from 2.5 to 2 [Figs. 3(a) and 3(b), respectively]. However, as $L_r/D_r$ is further reduced from 2 to 1, $x_{core}$ decreases to $\approx 60$ mm, with the distance between the ERZ vortex-core and the bluff end-wall ($\Delta x_{end}$) reduces to $\Delta x_{end} \approx 20$ mm. In addition, this decrease in the aspect ratio also increases the radial location of the ERZ core ($r_{core}$) from $r_{core} \approx 21$ mm at $L_r/D_r = 2.5$ to $r_{core} \approx 29$ mm at $L_r/D_r = 1$. These findings are attributed to the effect of jet impingement on the bluff end-wall that influences the development of the resulting flow and are consistent with a previous study employing an unconfined single jet. Hence, it can be concluded that the position of the ERZ exhibits a strong dependence on the aspect ratio $L_c/D_c$ for low-swirl configurations ($\theta_j = 5^\circ$), which is most significant for $L_c/D_c < 2$.

Figures 3(a)–3(d) also show that a reduction in the aspect ratio $L_r/D_r$ leads to a significant increase in the velocity magnitude of the inlet-jets upstream from the merging point. For example, the velocity near the merging point increases by $\approx 35\%$ from $L_c/D_c = 2.5$ [Fig. 3(a)] to $L_c/D_c = 1$ [Fig. 3(d)]. Since the inlet-jet parameters ($\alpha_j$, $\theta_j$, and $U_e$) are identical to all cases, the increased value in $U_e/U_e$ is attributed primarily to a reduction in the flow oscillation at and upstream from the merging point as $L_r$ is decreased. This reduction in flow unsteadiness, such as jet flapping or precessing, is addressed later in the paper and has also been widely reported previously for multiple-jet configurations. For the current MJCC configurations, a shorter length of the chamber tends to restrict both the “in-plane” and “out-of-plane” motions of the four inlet-jets, which therefore inhibits the flow oscillation that is associated with the interaction between inlet-jets. In addition, the reduction in the chamber length also increases the velocities in the ERZ, reducing the rate of decay in the jets upstream from the merging point.

For the higher-swirl cases with $\theta_j = 15^\circ$ [Figs. 3(e)–3(h)], the ERZ is much shorter and a central recirculation zone (CRZ) also occurs within the measurement region so that no central resulting jet is generated. Instead the flow bifurcates to form a conically divergent resulting flow downstream from the merging point. The cores of the ERZ and CRZ are marked with a white “×” and a white “+,” respectively. It can be seen that the axial and radial locations of the vortex-core within the ERZ region remain constant at $x_{core} \approx 56$ mm and $r_{core} = 25$ mm, respectively, regardless of $L_r/D_r$. By contrast, $x_{core}$ within the CRZ moves upstream from $x_{core} \approx 95$ mm to $x_{core} \approx 86$ mm as $L_r/D_r$ is reduced from 2.5 to 1.5. Importantly, as $L_r/D_r$ is further reduced to 1, the downstream CRZ is no longer observed within the chamber due to insufficient space. The vortex-core of the ERZ at $L_r/D_r = 1$ moves slightly to further downstream ($x_{core} \approx 58$ mm), implying that $L_r/D_r$ influences the ERZ for this case. This also suggests that the dependence of the ERZ on $L_r/D_r$ will be increased if $L_r/D_r$ is further reduced (e.g., $L_r/D_r < 1$). Hence, for the configurations with large azimuthal angle ($\theta_j = 15^\circ$), the upstream ERZ region is almost independent of the value of $L_r/D_r$ for $L_r/D_r \geq 1.5$ but becomes significant for $L_r/D_r < 1.5$, while the downstream CRZ region depends strongly on all values of $L_r/D_r$ considered here.

Figure 4 presents the evolution of normalized mean axial velocity along the axis ($U_c/U_e$) for all MJCC configurations investigated here. The PIV data from our previous work of $L_r/D_r = 3$ are also included. Each mean velocity measurement has been performed from the time-average of the 1900 PIV image pairs. In each figure, the dashed line denotes the value of $U_c/U_e = 0$, while the dotted lines color-matched with data points refer to the locations of the bluff end-wall. The jet merging point, $P_{mer}$, refers to the location of the maximum velocity along the centerline of the chamber ($U_c/U_e$ max), the stagnation point, $P_s$, as the most upstream axial location of the velocity zero-crossing ($U_c/U_e = 0$), which also denotes the most downstream location of the resulting flow, and the point of the minimum axial velocity, $P_{min}$, as the axial location of the minimum velocity ($U_c/U_e$ min).

For the configurations of $\theta_j = 5^\circ$ [Fig. 4(a)], it can be seen that a decrease in the aspect ratio $L_r/D_r$ does not change the magnitude or location of $U_c/U_e$ at the merging point, with ($U_c/U_e$ max) $= 0.26$ at $x_{core} = 0.27$ for all cases. However, downstream from the merging point, the evolution of $U_c/U_e$ is strongly influenced by $L_r/D_r$. For example, as $L_r/D_r$ reduces from 2.5 to 1.5, the location of the stagnation point moves upstream from $x_{core} = 0.65$ to 0.5, while the decay of $U_c/U_e$ decreases significantly for $L_r/D_r = 1.5$. This is possibly caused by the effect of the end-wall on the development of central resulting jet flow that reduces the entrainment rate between the jet and surrounding fluids. Importantly, large data fluctuations were found at $x/L_r \approx 0.48$, with $RMS \approx 0.037$ for the case of $L_r/D_r = 1.5$, which is consistent with the strong gradients caused by the combined effects of a radial outlet flow, a bluff end-wall, and a cylindrical chamber. In addition, for $L_c/D_c = 1$ where the bluff end-wall closely approaches the location of the merging point, the central resulting flow is almost absent [see also Fig. 3(d)] due to the confinement effect from the cylindrical walls, while the decay of $U_c/U_e$ is the highest for all cases. Hence, it can be concluded that, for the case of $\theta_j = 5^\circ$, reducing the aspect ratio $L_r/D_r$ significantly inhibits the axial development of the central resulting flow for $L_r/D_r < 2$. 
For the \( \theta_j = 15^\circ \) case [Fig. 4(b)], it can be seen that the evolution of \( U_e/U_c \) along the axis is almost independent from \( L_c/D_e \). The value of \( (U_e/U_c)_{\text{max}} \) is approximately 0.1 at \( x/L_c = 0.21 \), while \( (U_e/U_c)_{\text{min}} \) is approximately 0.05 at \( x/L_c = 0.37 \) for the cases of \( L_c/D_e = 2-3 \). This shows that the locations of both the merging and stagnation points are independent from \( L_c/D_e \) for these cases. However, as the value of \( L_c/D_e \) reduces to 1.5, the location of the merging point moves slightly upstream (from \( x/L_c = 0.22 \) to 0.19), while magnitude of \( (U_e/U_c)_{\text{max}} \) reduces by 15\%. The axial extent of the negative velocity flow \( (U_e/U_c < 0) \) was also found to be reduced due to a shorter \( L_c \), although both the magnitude and location of \( (U_e/U_c)_{\text{min}} \) remain the same. For the shortest \( L_c \) considered here \( (L_c/D_e = 1) \), no negative velocity region is present owing to the absence of the CRZ [see also Fig. 3(h)]. In addition, the location of the merging point progresses further downstream to \( x/L_c = 0.24 \), while the value of \( (U_e/U_c)_{\text{max}} \) increases to 0.15 for \( L_c/D_e = 1 \). This indicates an increase in the size and intensity of the ERZ for \( L_c/D_e = 1 \), which also highlights the effect of the bluff end-wall on the development of divergent resulting flow. Hence, for the \( \theta_j = 15^\circ \) case, the aspect ratio of \( L_c/D_e \) can influence the flow characteristics within the CRZ for \( L_c/D_e > 1 \) or within the ERZ for \( L_c/D_e < 2 \).

Overall, the evolution of \( U_e/U_c \geq 0 \) is almost independent from the value of the chamber length \( L_c \) before the resulting flow approaches the bluff end-wall of the chamber, while this dependence increases significantly as \( L_c \) is further reduced. This is also consistent with the qualitative flow patterns in Fig. 3 as both the recirculation regions and resulting flow are changed for certain values of \( L_c \) depending on the configurations. Taken together, it can be concluded that the mean velocity field exhibits a strong dependence on the axial location of the resulting flow.

Figure 5 presents the evolution of the inverse mean axial velocity of the central resulting jet flow \( (U_e/U_c) \) as calculated on the equivalent axial coordinate from the jet origin

\[
x^e = x_0 + (x - x_{\text{mer}}),
\]

where \( x_{\text{mer}} \) denotes the distance between the throat and merging point and \( x_0 \) denotes the distance along the local axis of each jet between the pipe exit and merging point (see also the inset of Fig. 5). The cases with \( \theta_j = 15^\circ \) are not reported due to the absence of a resulting jet flow along the centerline of the chamber. However, the data for \( L_c/D_e = 3 \) and \( \theta_j = 0^\circ \) reported previously for non-swirled jets are included as a reference, and also included are the free pipe jet data of Xu and Antonia representing the unconfined single jet case. The axial coordinate is normalized by the equivalent jet exit diameter,

\[
D_e = \sqrt{N_j D_{\text{pipe}}},
\]

where \( N_j \) denotes the number of jets and \( D_e \) is the diameter of an equivalent circular pipe with the same exit area as the four inlet pipes. Here the merging and stagnation points \( (P_{\text{mer}} \text{ and } P_{\text{st}}) \) denote the most upstream and downstream of the resulting flow, respectively. It can be seen that, for all cases with a non-zero azimuthal angle \( (\theta_j > 0^\circ) \), the decay of \( U_e/U_c \) along the
centerline of the chamber is significantly greater than the non-swirled jet ($\theta_j = 0^\circ$) or single jet ($N_j = 1$) configurations within $8 \leq x' / D_e \leq 16$, regardless of the value of $L_c / D_e$. This is due to the presence of $\theta_j$ that increases the “out-of-plane” motion from the inlet jets, which implies that the additional azimuthal angle of the multiple-jet configurations substantially increases the centerline velocity decay of the resulting flows.

Figure 5 also shows that, for the configurations with $\theta_j = 5^\circ$, a decrease in $L_c / D_e$ from 3 to 2 leads to a decrease of only 5% in the rate of decay, i.e., $\Delta(U_j U_e) / \Delta(x' / D_e)$, while a decrease in $L_c / D_e$ from 2 to 1.5 leads to a decrease in the rate of decay by up to 40% at $x' / D_e = 13$. The rate of centerline decay has long been used as a measure of rate at which the jet flow exchanges momentum with the surrounding flow.\(^{37}\) Hence this step-change reduction at shorter chambers indicates a step change in the intensity of the ERZ. However, for the shortest chamber length considered here ($L_c / D_e = 1$), the rate of decay is the highest $[\Delta(U_j U_e) / \Delta(x' / D_e) \approx 4]$, with $U_j U_e \approx 8.5$ at $x' / D_e \approx 9$. This is due to the insufficient space downstream from the merging point, which causes the distance between the merging and stagnation points to approach zero $[(x_{Ps} - x_{mer}) \approx 0]$, implying that the resulting flow is almost absent. Hence, it can be concluded that the rate of decay of central resulting flow depends strongly on the distance between the merging and stagnation points—for the low-swirl configurations ($N_j = 25^\circ$ and $\theta_j = 5^\circ$) considered here.

B. Turbulent flow fields

Figure 6 presents the evolution of the axial RMS ($u'$) and radial RMS ($v'$) velocities, normalized by the nozzle exit velocity ($U_e$), along the centerline of the MJICC for all experimental conditions. Note that the legends are identical to all cases with the same $\theta_j$ for all figures in the paper. For the $\theta_j = 5^\circ$ cases [Figs. 6(a) and 6(b)], it can be seen that a decrease in $L_c / D_e$ leads to a substantial decrease ($\approx 20\%$) in both $u' / U_e$ and $v' / U_e$, particularly where $L_c / D_e \leq 1.5$. This suggests that the flow unsteadiness is substantially reduced as the chamber length is decreased. However, for the $\theta_j = 15^\circ$ cases [Figs. 6(c) and 6(d)], both the magnitudes of $u' / U_e$ and $v' / U_e$ are almost independent from $L_c$ for all aspect ratios investigated here, while the difference in the magnitude of $u' / U_e$ and $v' / U_e$ is typically within 10%. This weaker dependence of the centerline velocity fluctuations on $L_c / D_e$ for $\theta_j = 15^\circ$ than for $\theta_j = 5^\circ$ provides further evidence of the reduced influence of the chamber aspect ratio on flow unsteadiness (e.g., precession) for higher azimuthal angles.

It is also worth noting that for both $\theta_j = 5^\circ$ and $\theta_j = 15^\circ$ configurations, a significant reduction in $u' / U_e$ and an increase in $v' / U_e$ were measured in the region where the resulting flow approaches the bluff end-wall ($\approx 5\%$ of the total length of $L_c$ before the end-wall). This is most significant for the cases where $L_c / D_e = 1.5$. That is, the impingement of the resulting flow on the bluff end-wall acts both to amplify the velocity fluctuations in the radial direction ($v'$) and to inhibit the axial velocity fluctuations ($u'$) within the impingement region.

The results in Figs. 4–6 show that both the mean and RMS flow-fields are typically independent from the value of $L_c / D_e = 3$. Hence, subsequent analyses are performed only for the range of $1 \leq L_c / D_e \leq 2.5$.

Figure 7 presents the radial profiles of the mean axial ($U_j$), axial RMS ($u'$), and radial RMS ($v'$) velocities, normalized by the nozzle exit velocity ($U_e$), at the jet merging point for all experimental conditions. (The $L_c / D_e = 3.0$ case was not included here because the measurements are almost identical to the $L_c / D_e = 2.5$ case.) The results in Fig. 7(a) show that, for the $\theta_j = 5^\circ$ cases, the value of $U_j / U_e$ at the merging point is almost independent from the chamber length for $1 \leq L_c / D_e \leq 2.5$. The peak mean velocity ($U_j / U_e$)$_{\text{max}}$ occurs on or near to the central axis, while the region of negative velocity is typically limited to $r / D_e \geq 0.3$ for all cases. This indicates that the radial extent of the ERZ does not change significantly with the value of $L_c / D_e$ for $L_c / D_e > 1$. However, as $L_c / D_e$ is decreased to 1, the magnitude of velocity within $r / D_e \geq 0.2$ increases by approximately 10% and the radial location of negative velocity extends to $r / D_e \geq 0.4$. This highlights the influence of the bluff end-wall on the flow field at and around the merging point for all cases.
FIG. 6. Evolution of the axial RMS ($u'$) and radial RMS ($v'$) velocities, normalized by the nozzle exit velocity ($U_e$), along the centerline of the MIJCC for the cases of (a) and (b) $\alpha_j = 25^\circ$ and $\theta_j = 5^\circ$, (c) and (d) $\alpha_j = 25^\circ$ and $\theta_j = 15^\circ$, and for aspect ratios of $L_c/D_c = 1–3$. For clarity, only one in two data points is presented and the legends are identical to all cases with the same $\theta_j$.

The results in Figs. 7(b) and 7(c) also show that a decrease in $L_c/D_c$ leads to a maximum reduction of 20% in the value of $u'/U_e$, while the value of $v'/U_e$ remains almost independent from the $L_c/D_c$. The location of $(u'/U_e)_{\text{max}}$, which corresponds well with the maximum value of the mean velocity gradient presented in Fig. 7(a), moves from $r/D_c \approx 0.16$ to $r/D_c \approx 0.09$ and its magnitude decreases from $(u'/U_e)_{\text{max}} \approx 0.12$ to $\approx 0.09$ as $L_c/D_c$ is decreased from 2.5 to 1. However, the value of $(v'/U_e)_{\text{max}}$ is approximately 0.08 at the central axis ($r/D_c = 0$) for all cases. This indicates that a decrease in $L_c/D_c$ from 2.5 to 1 tends to inhibit the axial velocity fluctuation but not to influence significantly the radial velocity fluctuation at the merging point. As a large fluctuation of velocity is commonly associated with flow unsteadiness, this provides further evidence that decreasing the aspect ratio tends to reduce the flow unsteadiness within the jet-interaction region for low-swirl configurations ($\alpha_j = 25^\circ$ and $\theta_j = 5^\circ$).
For the $\theta_j = 15^\circ$ configurations, the velocity peak $(U_r/U_e)_{max}$ occurs at $r/D_c \approx 0.1$ for all cases [Fig. 7(d)]. It can also be seen that the mean axial velocity decreases slightly as $L_c/D_c$ is decreased from 2.5 to 1.5, with a maximum 20% reduction in $U_r/U_e$ at $r/D_c \approx 0.1$. However, the value of $U_r/U_e$ increases significantly as $L_c/D_c$ is further reduced to 1, and the maximum increase is around 70% within $r/D_c \geq 0.2$. The trend of an increased $U_r/U_e$ for the case where $L_c/D_c$ approaches 1 is possibly caused by the increased strength of the divergent resulting flow for $\theta_j = 15^\circ$ cases, as shown qualitatively in Fig. 3.

The radial profiles of RMS velocities in Figs. 7(e) and 7(f) show that the effect of $L_c/D_c$ on the velocity fluctuations is non-linear since both the values of $u'/U_e$ and $v'/U_e$ decrease as $L_c/D_c$ is decreased from 2.5 to 1.5 and then increase as $L_c/D_c$ is further decreased to 1. Interestingly, the CRZ is detected for $L_c/D_c \geq 1.5$, but not for $L_c/D_c = 1$ (see also Fig. 3). This suggests that the presence of a CRZ damps velocity fluctuations in the high-swirl configurations ($\theta_j = 15^\circ$). Nevertheless, the case $L_c/D_c = 1$ has a different trend to the other cases in the mean and RMS velocity fields due to the absence of the central resulting jet flow for $\theta_j = 5^\circ$ configurations or the CRZ region for $\theta_j = 15^\circ$ configurations.

Overall, it can be concluded that a decrease in the aspect ratio $L_c/D_c$ leads to a decrease in velocity fluctuations for most cases, although the effects are non-linear. That is, increasing $L_c/D_c$ in this range tends to increase interaction with the wall, and hence the amplification of large-scale eddies in the flow.

Figure 8 presents the radial profiles of the ratio of axial and radial RMS velocities ($u'/v'$) and the Reynolds shear stresses ($uv'/U_e^2$) at the merging point for all experimental conditions. For the configurations of $\theta_j = 5^\circ$ [Fig. 8(a)], it can be seen that the value of $u'/v'$ exhibits two peaks, one in the shear layer ($r/D_c \approx 0.15$), consistent with an unconfined single jet,38 and the other in the near wall region ($r/D_c \approx 0.45$). These locally high values imply a high degree of anisotropy in these regions, consistent with an important role of large-scale turbulence. In addition, a decrease in $L_c/D_c$ tends to reduce the value of $u'/v'$ along the cylinder radius ($r$), with the most significant reduction occurring for $L_c/D_c = 1$. By contrast, for the configurations where $\theta_j = 15^\circ$ [Fig. 8(b)], the value of $u'/v'$ typically varies between 1.5 and 1 for all cases, so that the effect of $L_c/D_c$ on $u'/v'$ is relatively small. This indicates that, first, the variation of anisotropy at the merging point is more significant for $\theta_j = 5^\circ$ than for $\theta_j = 15^\circ$, regardless of the value of $L_c/D_c$, and second, the influence of $L_c/D_c$ on the anisotropy is more significant for the ERZ dominated regime ($\theta_j = 5^\circ$) than for the CRZ dominated regime ($\theta_j = 15^\circ$).

Figures 8(c) and 8(d) also show that a decrease in $L_c/D_c$ leads to a decrease in the Reynolds stresses at the merging point for both the $\theta_j = 5^\circ$ and $\theta_j = 15^\circ$ configurations, although it is most significant for $\theta_j = 5^\circ$. This provides further evidence that reducing $L_c/D_c$ reduces large-scale interactions between
the jet and surrounding flow within the jet interaction region. However, the value of $\langle uv \rangle / U_c^2$ is typically greater for the higher-swirl cases than that for the low-swirl cases. That is, although the degree of anisotropy at the merging point is greater for $\theta_j = 5^\circ$, the extent of large-scale flow motion at this point is greater for $\theta_j = 15^\circ$ than that for $\theta_j = 5^\circ$, regardless of the value of $L_c/D_c$. This evidence supports the finding that the interaction between multiple jets is stronger for high-swirl jet configurations.

Figure 9 presents the integral length scale normalized by the nozzle diameter ($L_u/D_{\text{pipe}}$) along the centerline of the MIJCC for all experimental conditions. The integral length scale...
The recirculation rate $K_r$ is defined as

$$K_r = \frac{m_{ent}}{m_{in}},$$

where $m_{ent} = \int_0^\infty 2\pi r \rho U_{ent} dr$

is the total mass flow rate of fluid entrained by all inlet jets transported upstream through a plane orthogonal to the axis at the plane $x/L_r$.

Equation (5) was adapted from the calculation of the entrainment rate from the previous study of the jet.\(^{41-43}\) where the entrainment velocity, $U_{ent}$, refers to the negative axial velocity ($U_\infty < 0$) within the chamber, while the positive axial velocity was excluded from the calculation. The symbol of $m_{ent}$ refers to the total inlet mass flow rate of fluid.

For the $\theta_j = 5^\circ$ configurations [Fig. 10(a)], the results show that a single hump profile, approximately corresponding to the axial extent of the ERZ, occurs for all cases, while the location of peak $K_r$ [$K_r^{max.ERZ}$] coincides well with the location of the vortex-core in the ERZ ($x_{core}$ in Fig. 3).

For $L_c/D_c = 2.5$–1.5, a decrease in $L_c/D_c$ tends to decrease the value of $K_r$ throughout the chamber, although $K_r^{max.ERZ}$ for all three cases remains approximately the same (occurring at $x/L_r = 0.38$). However, for $L_c/D_c = 1$, $K_r^{max.ERZ}$ increases significantly (by 25%) and its location moves further upstream to $x/L_r = 0.2$ due to the confinement effect caused by the chamber length. Hence, the axial profile of $K_r$ is consistent for $L_c/D_c \geq 2$, while as $L_c$ is further reduced to 1, both the value and distribution of $K_r$ are strongly restricted by the reduced chamber length.

The results in Fig. 10 also show that the value of $K_r^{max.ERZ}$ for all cases considered here, regardless of $L_c/D_c$. This is an important finding for the development of practical combustion applications, particularly those employing combustion in the MILD (moderate or intense low-oxygen dilution) regime because it implies the presence of a large and uniform recirculation zone, which is important for the MILD combustion regime, suggesting strong potential for a quasi-homogeneous temperature.\(^{28,30}\)
D. Effects of the chamber aspect ratio

Table IV presents a summary of the location of the jet merging point ($x_{mer}/L_c$), stagnation point ($x_{s}/L_c$), and the CRZ axial extent ($x_{CRZ}/L_c$) along the axis of the MIJCC for all chamber aspect ratios investigated in the present study. Here $x_{CRZ}$ denotes the maximum axial location of the CRZ region. It can be seen from the table that all critical locations change significantly as the $L_c/D_c$ is reduced.

Figure 11 presents the characteristic centerline length of (a) the stagnation point ($\Delta x_s$), (b) the CRZ region ($\Delta x_{CRZ}$), and (c) the ERZ region ($\Delta x_{ERZ}$), normalized by the diameter of the chamber ($D_c$), as a function of the aspect ratio $L_c/D_c$. As shown in the inset, we define $\Delta x_s = (L_c - x_s)$ as the distance between the stagnation point and the bluff end-wall, $\Delta x_{CRZ} = (x_{CRZ} - x_s)$ refers to the distance between the merging and stagnation points, and $\Delta x_{ERZ} = (x_{CRZ} - x_c)$ denotes the distance between the stagnation and CRZ points. The data points for $L_c/D_c = 3$, which were measured from our previous study but not previously published, are also included. All measured data points are labelled with solid markers, while some “extrapolated” points, which are labelled with hollow markers, are extrapolated from the values in Table IV.

For Fig. 11(a), it can be seen that $\Delta x_s$ increases linearly with the aspect ratio $L_c/D_c$ in the range $1 \leq L_c/D_c \leq 3$ for the high-swirl cases ($\theta_j = 15^\circ$) and $2 \leq L_c/D_c \leq 3$ for the low-swirl cases ($\theta_j = 5^\circ$). For the latter case, the value of $\Delta x_s \approx 0$ occurs for $L_c/D_c \leq 2$, which suggests that $L_{c, crit}/D_c = 2$ is the critical chamber length where the bluff end-wall starts to significantly impact the ERZ and the resulting flow. Conversely, it can also be inferred that for $L_c > L_{c, crit}$, the chamber length does not significantly influence the ERZ within the cylindrical chamber. For the higher-swirl cases ($\theta_j = 15^\circ$), the values of $\Delta x_s$ are larger than the low-swirl cases due to the decreased axial extent of the ERZ. Hence, the value of $L_{c, crit}$ is approximately equal to $D_c$ for these configurations ($L_{c, crit}/D_c = 1$).

The trends for $\Delta x_{CRZ}$ in Fig. 11(b) are qualitatively similar to those for $\Delta x_s$. That is, a decrease in the aspect ratio $L_c/D_c$ significantly decreases the value of $\Delta x_{CRZ}/D_c$ for both the $\theta_j = 5^\circ$ and $\theta_j = 15^\circ$ configurations. The value of $\Delta x_{CRZ}/D_c$ reduces from $0.45$ at $L_c/D_c = 3$ to $0$ at $L_c/D_c = 2$ for $\theta_j = 5^\circ$ configurations, while for $\theta_j = 15^\circ$ cases, the value of $\Delta x_{CRZ}/D_c$ decreases from $1.55$ at $L_c/D_c = 3$ to $0$ at $L_c/D_c = 1$. The value of $\Delta x_{CRZ}/D_c$ is important for quantifying the effect of $L_c/D_c$ on the CRZ region since the critical value of $\Delta x_{CRZ, crit}/D_c = 0$ indicates the absence of the CRZ within the cylindrical chamber. Hence, a decrease in the value of $L_c/D_c$ from $3$ to $1$ leads to a reduction in the size of the CRZ for both configurations.

![Figure 11](image_url)

**TABLE IV.** Normalized axial location of the jet merging and stagnation points, and the CRZ axial extent along the centerline of the MIJCC.

| Experiment case no. | Configurations | Jet merging point ($x_{mer}/L_c$) | Stagnation point ($x_{s}/L_c$) | CRZ point ($x_{CRZ}/L_c$) |
|---------------------|----------------|---------------------------------|-----------------------------|--------------------------|
| 1                   | MIJCC-05-LD25  | 0.27                            | 0.65                        | >0.65                    |
| 2                   | MIJCC-05-LD20  | 0.27                            | 0.65                        | N/A                      |
| 3                   | MIJCC-05-LD15  | 0.27                            | 0.50                        | N/A                      |
| 4                   | MIJCC-05-LD10  | 0.27                            | 0.33                        | N/A                      |
| 5                   | MIJCC-15-LD25  | 0.21                            | 0.29                        | >0.65                    |
| 6                   | MIJCC-15-LD20  | 0.21                            | 0.29                        | 0.65                     |
| 7                   | MIJCC-15-LD15  | 0.19                            | 0.27                        | 0.48                     |
| 8                   | MIJCC-15-LD10  | 0.24                            | 0.32                        | N/A                      |
| 9                   | MIJCC-05-LD30  | 0.27                            | 0.65                        | >0.65                    |
| 10                  | MIJCC-15-LD30  | 0.21                            | 0.28                        | >0.65                    |
while the absence of the CRZ region occurs for \( L_c/D_c \leq 2 \) and 1 for \( \theta_j = 5^\circ \) and 15\(^\circ\) configurations, respectively.

It can also be seen from Fig. 11(c) that for \( \theta_j = 5^\circ \) configurations, the value of \( \Delta x_{ERZ}/D_c \) significantly decreases from 1.2 to 0.1 as \( L_c/D_c \) is further decreased to 1. By contrast, the value of \( \Delta x_{ERZ}/D_c \) is almost independent of \( L_c/D_c \) within the range of 1 \( \leq L_c/D_c \leq 3 \) for \( \theta_j = 15^\circ \) configurations. This is because the bluff end-wall only impacts the upstream ERZ for \( L_c/D_c \leq 1 \) due to the shorter axial extent of the ERZ for \( \theta_j = 15^\circ \). The parameter of \( \Delta x_{ERZ}/D_c \) quantifies the effect of the aspect ratio \( L_c/D_c \) on both the ERZ and the jet merging point, which means that for the cases where \( \Delta x_{ERZ}/D_c \) approaches 0, the inlet-jets impinge on the bluff end-wall instead of generating a resulting flow. Hence, the value of \( L_c/D_c \) significantly influences the interaction of multiple jets for \( L_c/D_c \leq 1 \), for all values of \( \theta_j \).

It is also worth noting that, for the values of \( L_c/D_c \) considered here, a reduction in \( L_c/D_c \) leads to a significant decrease in the difference between the values of \( \Delta x_{ERZ}/D_c \) and \( \Delta x_{CRZ}/D_c \) for both the \( \theta_j = 5^\circ \) and \( \theta_j = 15^\circ \) configurations. For example, the difference in \( \Delta x_{ERZ}/D_c \) between \( \theta_j = 5^\circ \) and \( \theta_j = 15^\circ \) reduces from \( \Delta(x_{ERZ}/D_c) = 1.1 \) at \( L_c/D_c = 3 \) to \( \Delta(x_{ERZ}/D_c) = 0 \) at \( L_c/D_c = 1 \). This, in turn, suggests that as the aspect ratio \( L_c/D_c \) is reduced from 3 to 1, the significance of \( L_c/D_c \) on the larger-scale recirculation zones within the MIJCC increases, while the significance of \( \theta_j \) decreases substantially.

### E. Identification of the key controlling parameters for flow regimes

Table V summarizes the key parameters for controlling the three distinctive flow regimes that have been identified within the rotationally symmetric MIJCC configurations for a fixed value of \( \alpha_j = 25^\circ \) but with \( \theta_j = 5^\circ \) and 15\(^\circ\), and a decrease value of the chamber aspect ratio \( L_c/D_c \) from 3 to 1, using both the flow visualization and quantitative data. The three flow regimes are shown schematically in Fig. 12, and the detailed description are presented in Secs. III E 1–III E 3.

1. **Regime I: External and central recirculation zones**

Regime I is characterized by the presence of both external and central recirculation zones [ERZ (red dashed box) and CRZ (purple dotted box)] within the MIJCC. The relative significance of the ERZ and CRZ depends strongly on the value of jet angles (\( \alpha_j \) and \( \theta_j \)), which is consistent with our previous work,\(^{10,11}\) while the aspect ratio \( L_c/D_c \) has a negligible influence on the large-scale flow structure in this regime.

2. **Regime II: External recirculation zone with a resulting flow**

Regime II is characterized by the presence of a dominant ERZ generated from the resulting flow within the MIJCC. The effect of the aspect ratio \( L_c/D_c \) significantly reduces the position and strength of the ERZ due to the increased confinement.
caused by the bluff end-wall. The influence of jet angles ($\alpha_j$ and $\theta_j$) remains significant in this regime, although it is not as prominent as that in Regime I.

3. Regime III: External recirculation zone with no resulting flow

Regime III is characterized by the presence of dominant ERZ generated from the multiple inlet-jets, which runs the entire chamber of the MIJCC. Owing to the significantly reduced value in $L_c/D_c$, the inlet-jets have insufficient space to generate a resulting flow downstream from the merging point. Therefore, the size of the ERZ is further reduced and the strength of the ERZ is the strongest.

Figure 13 presents a regime map as a function of the chamber aspect ratio $L_c/D_c$ and jet azimuthal angles ($\theta_j$) for the MIJCC configurations of $\alpha_j = 25^\circ$. It can be seen that the transition between each regime occurs for $L_c/D_c \approx 2$ and 1 for $\theta_j = 5^\circ$ configurations, and $L_c/D_c \approx 1$ and $<1$ for $\theta_j = 15^\circ$ configurations. This implies that a higher value of $\theta_j$ reduces the critical value of $L_c/D_c$. This is because a higher value of $\theta_j$ results in less impingement among inlet-jets, a weaker resulting flow, and a higher swirl, which in turn decreases the axial extent of the ERZ and CRZ. Hence, it can be concluded that, for both the low-swirl ($\theta_j = 5^\circ$) and high-swirl ($\theta_j = 15^\circ$) configurations, the flow patterns are strongly controlled by the combination of the jet azimuthal angle ($\theta_j$) and the chamber aspect ratio ($L_c/D_c$), with the significance of $L_c/D_c$ increases as $L_c/D_c$ decreases.

IV. CONCLUSIONS

New quantitative information has been provided on the iso-thermal flow field within a cylindrical chamber featuring multiple jets with an inclination angle $\alpha_j = 25^\circ$ and two azimuthal angles $\theta_j = 5^\circ$ and $15^\circ$ for a range of chamber aspect ratios ($L_c/D_c$). Three distinctive flow regimes were identified within the Multiple Impinging Jet in a Cylindrical Chamber (MIJCC) as follows:

a. Regime I ($L_c/D_c > 2$ for $\theta_j = 5^\circ$ or $L_c/D_c > 1$ for $\theta_j = 15^\circ$): External and central recirculation zones.

b. Regime II ($L_c/D_c > 1$ for $\theta_j = 5^\circ$ or $L_c/D_c = 1$ for $\theta_j = 15^\circ$): External recirculation zone with a distinctive resulting flow.

c. Regime III ($L_c/D_c \leq 1$ for $\theta_j = 5^\circ$ or $L_c/D_c < 1$ for $\theta_j = 15^\circ$): External recirculation zone with no resulting flow.

The key findings of the study are as follows:

1. The presence of each flow regime is strongly controlled by the combination of the jet angles ($\alpha_j$ and $\theta_j$) and the chamber aspect ratio ($L_c/D_c$), with the significance of $L_c/D_c$ increases as the value of $L_c/D_c$ is decreased from 3 to 1.

2. The flow field within the ERZ immediately downstream from the jet merging point in Regime I is approximately independent of the length of the cavity $L_c$. However, in Regimes II and III, the characteristics of the ERZ depend strongly on $L_c$.

3. For $\theta_j > 0^\circ$ cases, the decay of the central resulting flow downstream from the jet merging point is significantly greater than for $\theta_j = 0^\circ$ (single jet or multiple jets). The value of mean axial velocity ($\langle U_x \rangle$) along the axis of the chamber was found to increase by approximately 40% from Regime I to Regime II, while it decreases significantly (by 50%) for Regime III. This indicates that the effect of the aspect ratio $L_c/D_c$ depends strongly on the presence or absence of the resulting flow downstream from the merging point.

4. The significance of the large-scale oscillations (e.g., jet precession) and the velocity fluctuations ($u'$ and $v'$) was found to increase with the chamber aspect ratio $L_c/D_c$ for those configurations where the ERZ is dominant ($\theta_j = 5^\circ$). However, the influence of $L_c/D_c$ on flow unsteadiness was found to be relatively small for those configurations generating a dominant CRZ ($\theta_j = 15^\circ$). This is evidenced by a higher value of Reynolds shear stress ($\langle uv \rangle/U_x^2$) for all $L_c/D_c$ cases at the merging point for $\theta_j = 15^\circ$ than for $\theta_j = 5^\circ$.

5. The large-scale flow motion corresponding to the integral length scale ($L_u$) was found to be inhibited as $L_c/D_c$ is decreased for the case where a swirl is relatively weak ($\theta_j = 5^\circ$), while it is almost independent from $L_c/D_c$ for higher-swirl cases ($\theta_j = 15^\circ$). This indicates a reduced influence of the chamber aspect ratio on the turbulent velocity field for $\theta_j = 15^\circ$ cases.

6. The value of the recirculation rate ($K_r$) was found to increase by 25% as $L_c/D_c$ is reduced from 3 to 1 (Regime I to Regime III), although the axial extent of $K_r$ reduces by 50%. The value of $K_r$ exceeds 3 for all cases, which has been found by others to be an important indicator for the avoidance of combustion reactants impinging on the walls and also maintaining a relatively high recirculation rate ($K_r \geq 3$).

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