Numerical Simulations of Isothermal Flow in a Swirl Burner

In this paper, the non-reacting flow in a swirl burner is studied using large eddy simulation. The configuration consists of two unconfined coannular jets at a Reynolds number of 81,500. The flow is characterized by a Swirl number of 0.93. Two cases are studied in the paper differing with respect to the axial location of the inner pilot jet. It was observed in a companion experiment (Bender and Büchner, 2005, Proc. 12 Int. Cong. Sound and Vibration, Lisbon, Portugal) that when the inner jet is retracted the flow oscillations are considerably amplified. This is also found in the present simulations. Large-scale coherent structures rotating at a constant rate are observed when the inner jet is retracted. The rotation of the structures leads to vigorous oscillations in the velocity and pressure time signals recorded at selected points in the flow. In addition, the mean velocities, the turbulent fluctuations, and the frequency of the oscillations are in good agreement with the experiments. A conditional averaging procedure is used to perform a detailed analysis of the physics leading to the low-frequency oscillations. [DOI: 10.1115/1.2364198]

Introduction

In recent years, there has been increased demand for gas turbines that operate in a lean premixed mode of combustion in an effort to meet stringent emission goals. Highly turbulent swirl-stabilized flames are often used in this context. However, swirling flows are prone to flow instabilities, which can trigger combustion oscillations and cause damage to the device. Lean premixed burners in modern gas turbines often make use of a richer pilot flame, which is typically introduced near the symmetry axis.

In order to prevent the appearance of undesired flow instabilities, it is necessary to understand the underlying physical phenomena. Several mechanisms have been identified in the literature as potential triggers of combustion instabilities. There is, however, no consensus about the real importance of each of them. Lieuwen et al. [1] suggested that heat-release oscillations excited by fluctuations in the composition of the reactive mixture entering the combustion zone are the dominant mechanism responsible for the instabilities observed in the combustor. Other authors [2,3] favor the in-phase formation and combustion of large-scale coherent vortical structures. In premixed combustors, these large-scale structures play an important role in combustion and heat-release processes by controlling the mixing between the fresh mixture and hot combustion products [4].

The formation of large-scale coherent structures is a fundamental fluid-dynamical problem, which must be understood also in the absence of combustion. Large eddy simulation (LES) is a particularly suitable approach for studying this problem. It allows the treatment of high-Reynolds-number flows and at the same time the explicit computation of these structures. If properly conducted, LES should have only limited sensitivity to modelling assumptions. In the context of swirling flows, LES was first applied by Pierce and Moin [5]. Wang et al. [6] performed LES of swirling flow in a dump combustor and studied the influence of the level of swirl on the mean flow and on turbulent fluctuations. LES has also been used in combination with other techniques like acoustic analysis; for example, Roux et al. [7] studied the interaction between coherent structures and acoustic modes and found important differences between iso-thermal and reactive cases.

In the present paper LES is used to study the iso-thermal flow in a swirl burner at two different configurations. The analysis of the results focuses on the strength and sensitivity of flow instabilities generating large-scale coherent structures. In [8,9] the present authors performed LES of an unconfined annular swirling jet. Instabilities leading to large-scale coherent structures were detected and identified to be responsible for the oscillations observed in the corresponding experiment.

Physical and Numerical Modeling

Experimental Configuration. In [11] a co-annular swirl burner was developed that allows the change of geometrical features over a wide range. The burner, depicted in Fig. 1, is composed of two co-annular jets, a central pilot jet and a concentrically aligned main jet, whose swirl can be adjusted individually. In the experimental conditions considered here, a radial swirler was used for generating the swirl in the main jet. For the central pilot jet, an axial swirler was used to generate a co-rotating flow.

A large number of experiments were performed with this burner in several configurations including iso-thermal and reactive cases [11,12]. For the iso-thermal flow without external forcing, it was observed that axial retraction of the central jet into the duct leads to an increased amplitude of flow oscillations reflected by audible noise. In order to investigate this phenomenon by means of LES, two cases were selected. In the first case the inner jet is not retracted, i.e., both jets exit at the same position. In the second case, the pilot jet is retracted by 40 mm. This retraction of the pilot jet generates a double expansion for the main jet (see Fig. 2).

In both cases the co-annular jets issue into an ambient of the same fluid, which is at rest in the experiment. The outer radius of the main jet, \( R = 55 \text{ mm} \), is used as the reference length. The reference velocity is the bulk velocity of the main jet \( U_b = 22.1 \text{ m/s} \) and the reference time is \( t_b = R/U_b \). The inner radius of the main jet is \( 0.63R \). For the pilot jet the inner radius is \( 0.27R \) and the outer radius is \( 0.51R \). The mass flux of the pilot jet is 10% of the total mass flow. The Reynolds number based on the bulk velocity of the main jet \( U_b \) and is \( Re = 81,000 \). The swirl number is defined as

\[
S = \frac{U_b}{R_b} \sqrt{\frac{\text{mass flux of the pilot jet}}{\text{mass flux of the main jet}}}\
\]

\[
S = \frac{U_b}{R_b} \sqrt{\frac{U_b}{U_a}} \approx \frac{U_b}{R_b} \sqrt{\frac{U_b}{U_a}}
\]
The simulations were performed with the in-house code LESOCC2 [13], which is a successor of the code LESOCC [14]. It solves the incompressible Navier-Stokes equations on curvilinear block-structured grids. A collocated finite-volume discretization with second-order central schemes for convection and diffusion terms is employed. Temporal discretization employs the Rhie and Chow momentum interpolation [15] applied to avoid pressure-correction equation in the last stage only. The Rhie and Chow momentum interpolation [15] is applied to avoid pressure-flux of this stream. No-slip conditions were applied at solid walls. The fluid entrained by the jet is fed in by a mild co-flow of 5% of the average flow in an axial plane for both cases. It is well determined using an explicit three-dimensional box filter of width equal to twice the mesh size. The eddy viscosity was clipped to avoid negative values and was smoothed by temporal relaxation [17].

The computational domain extends 32R downstream of the burner exit located at x/R=0 and 12R in radial direction. It also covers part of the inlet ducts (Fig. 2). The block-structured mesh consists of about 8.5 million cells with 160 cells in azimuthal direction. The grid is stretched in both the axial and radial directions to allow for concentration of points close to the nozzle and the inlet duct walls. The stretching factor is everywhere less than 5%.

The specification of the inflow conditions for both jets requires a strong idealization. For the main jet, the way the swirl is introduced is not so critical because the swirler is located upstream, far away from the region of interest. Therefore, the flow is prescribed at the circumferential inflow boundary located at the beginning of the inlet duct (see Fig. 2). At this position steady top-hat profiles for the radial and azimuthal velocity components are imposed. This procedure was validated in [9]. The swirler of the pilot jet, on the other hand, is located directly at the jet outlet (Fig. 1). A numerical representation of this swirler would be very demanding because of the large number of blades and was therefore not considered in the present investigation. Instead, the inflow conditions for the pilot jet were obtained by performing simultaneously a separate, streamwise periodic LES of developed swirling flow in an annular pipe (see Fig. 2) using body forces to generate co-rotating swirl with S_pilot=2 as described in [18], where S_pilot is the swirl number of the pilot jet only. Recall that S_pilot has little impact on the swirl number of the entire flow due to the small mass flux of this stream. No-slip conditions were applied at solid walls. The fluid entrained by the jet is fed in by a mild co-flow of 5% of U_p. By using different values of the co-flow velocity it was shown in [19] that the flow development is not sensitive to this conditions. Free-slip conditions were applied at the open lateral boundary. A convective outflow condition was used at the exit boundary.

In both cases simulated, the same boundary conditions were employed. Figure 2 displays a zoom of the inflow region for x_pilot=−0.73R. In the case x_pilot=0, not shown here, the inflow region differs because the wall separating main and pilot jet and the cylindrical center body reach until x=0, with the inflow plane for the pilot jet still located at the same position x/R=−0.73. This is illustrated in Fig. 3.

**Average Flow**

After discarding initial transients, statistics were collected for 100t_b, which is long enough to obtain converged values in the near field of the burner. The averaging was performed in time and also along the azimuthal direction. Only resolved fluctuations are accounted for. It was checked, however, that the modelled subgrid-scale contributions are negligible [19].

**Streamlines.** Figure 3 shows the two-dimensional streamlines of the average flow in an axial plane for both cases. It is well known that at this high level of swirl a recirculation zone forms in the central region of the flow [20]. This phenomenon is related to the presence of a low pressure region on the symmetry axis. The influence of the retraction of the inner jet is remarkable. For x_pilot=0 the recirculation forms immediately behind the cylindrical center body and the length of the recirculation zone is about 9R. In the case x_pilot=−0.73R the length of the recirculation zone is only about 5R. The two streams mix before the final expansion and the recirculation is detached from the burner. The maximum width of the recirculation bubble is about 0.8R in both cases and it is attained at x/R=1.2 for x_pilot=0 and at x/R=1.5 for x_pilot=−0.73R. Far downstream of the jet exit, for x/R=6, the mean flow is not fully converged in the vicinity of the symmetry axis, as indicated by the wavy streamlines. The reason is that at this po-
sition the motions are slower and substantially longer averaging times would be necessary to obtain a fully converged mean flow.

Mean and RMS Velocity Profiles. A comparison of simulations with experiments is reported in Figs. 4–7, showing radial profiles of mean velocity and turbulent fluctuations at several axial stations for both cases.

The agreement with the experimental data is in general good for the mean flow. The case $x_{\text{pilot}}=0$ is well reproduced in the simulation (Fig. 4), which is noteworthy in spite of the strong idealization in setting up the inflow conditions for the pilot jet. The limited strength of the pilot jet can be appreciated by the mean axial and tangential velocity at $x/R=0.1$. In the case $x_{\text{pilot}}=-0.73R$ (Fig. 5), a discrepancy is evident at $x/R=0.1$; the backflow is overpredicted in the simulation. This implies that the recirculation zone in Fig. 3(b) does not correspond exactly to the experimental one, which was measured to be slightly further downstream. Nevertheless, other characteristics are very well predicted so that this simulation is still close to the experiment. For example, the spreading of the jet is in good agreement with the experiment and so are the turbulent fluctuations of axial and tangential velocity (Fig. 7). The agreement is also good for the turbulent fluctuations in the case $x_{\text{pilot}}=0$ (Fig. 6).

Some features are common in both cases. Apart from the presence of a recirculation zone, two complex shear layers subject to curvature effects are present in the flow. The inner shear layer is formed between the main jet and the recirculation zone. The outer shear layer is formed between the main jet and the surrounding co-flow. In the case $x_{\text{pilot}}=0$, the turbulent fluctuations generated in these layers are clearly visible up to $x/R=1$ in the profiles of RMS fluctuations by corresponding peaks (Fig. 6). In the case $x_{\text{pilot}}=-0.73R$ this feature is only observed in the profile of the axial fluctuations very close to the jet exit 7(a). Note also that the level of fluctuations at $x/R=0.1$ is much higher for $x_{\text{pilot}}=-0.73R$. In that case the maximum RMS is about $0.5U_b$, while in the case $x_{\text{pilot}}=0$ it does not reach $0.3U_b$. Further downstream at $x/R=3$ this difference has vanished and in both cases the maximum RMS fluctuation is close to $0.3U_b$, although the radial spreading of the profiles is larger in the case $x_{\text{pilot}}=-0.73R$.

Fluctuating Kinetic Energy. To conclude the description of the average flow, Fig. 8 displays contours of the fluctuating kinetic energy, using the same scale for both cases. It is obvious that the retraction of the pilot jet leads to a large increase in the level of the fluctuating energy. In the case $x_{\text{pilot}}=0$ the fluctuating kinetic energy is concentrated in the two shear layers mentioned above and the maximum level is $k_{\text{max}}/U_b^2\sim0.14$. In the case $x_{\text{pilot}}=-0.73R$ the kinetic energy is concentrated in three regions, just behind the inner part of the burner, at the beginning of the recirculation bubble (compare Figs. 8(b) and 3(b)), and in the region of the inner shear layer. As evidenced by the RMS profile of tangential velocity fluctuations (Fig. 7 at $x/R=0.1$ and radial fluctua-
tions, not shown here), showing a pronounced local maximum at the symmetry axis, these two components (radial and tangential) contribute mainly to the concentration of kinetic energy at the beginning of the recirculation zone. The features observed here will be discussed below in connection with the vortical structures present in the respective flows.

**Instantaneous Flow and Spectra**

**Coherent Structures.** For a swirling annular jet, large-scale coherent structures were identified and their evolution and interaction described in [8,9]. It was shown that two families of structures appear, an inner one oriented quasi-streamwise and located in the inner shear layer formed by the jet on its boundary with the recirculation zone (the so-called precessing vortex cores [20]), and an outer one oriented at a larger angle to the axis and situated in the outer shear layer formed on the boundary with the surrounding co-flow. Figure 9 shows iso-surfaces of pressure fluctuations $p''$ for both cases visualizing the coherent structures of the flow. Pressure fluctuations are more suitable for the visualization of coherent structures than the commonly used instantaneous pressure [21] because iso-surfaces of the latter are influenced by the spatially variable average pressure field, which is unrelated to instantaneous structures. Figures 9(a) and 9(c) display two different levels of $p''$ for the case $x_{pilot}=0$, namely $p''=-0.3$ and $p''=-0.15$, respectively. Figures 9(b) and 9(d) show the level $p''=-0.3$ at two different instants in time for the case $x_{pilot}=-0.73$. The color of the structures is given by the radial gradient of mean axial velocity. In the inner shear layer $(u_x)/Ur>0$ and the iso-surface

![Fig. 5 Radial profiles of mean velocity $x_{pilot}=-0.73R$. (a) Axial velocity. (b) Tangential velocity. Symbols, experiments [11]. Lines, LES.](image1)

![Fig. 6 Radial profiles of RMS velocity $x_{pilot}=0$. (a) Axial velocity. (b) Tangential velocity. Symbols, experiments [11]. Lines, LES.](image2)
is light colored. In the outer shear layer \( \partial(\mu_c)/\partial r < 0 \) and the iso-surface is dark colored.

Pronounced large-scale coherent structures are observed in the case of the retracted pilot jet (Figs. 9(b) and 9(d)). As in the case without inner jet [9], two structures can be observed in these pictures. Animations have shown that the rotation of the inner structure around the symmetry axis is very regular. At some instances, however, the inner structure branches lead to two arms as shown in Fig. 9(d). The leading one, in the direction of rotation, is faster than the second one and takes over in terms of strength. The one behind disappears at the exit in less than half a rotation period and in the downstream field during another half period. In the case without retraction, \( x_{\text{pilot}} = 0 \), the structures are substantially smaller and more irregular. In fact, if one compares the same level of pressure fluctuations \( p'' = -0.3 \), hardly any structure is visible in the flow (Fig. 9(a)). Increasing the pressure level to \( p'' = -0.15 \), small structures are visible, which exhibit small coherence. At this point it should be recalled that the same flow with just the pilot jet blocked shows substantial coherent structures, similar to the ones for \( x_{\text{pilot}} = -0.73R \) but somewhat weaker and less organized [8]. In the case \( x_{\text{pilot}} = 0 \), hence, the pilot jet destroys the large-scale structures. When the pilot jet is retracted to \( x_{\text{pilot}} = -0.73R \) this is not observed. The cylindrical tube enclosing the main jet prevents the recirculation bubble from moving upstream to the central bluff body containing the exit of the pilot jet. This holds for the mean flow (Fig. 3(b)) as well as for the conditionally averaged flow discussed later. The pilot jet therefore only “hits” the upstream front of the recirculation bubble but cannot penetrate into the inner shear layer where it would be able to impact on the coherent structures. The different coherent structures observed in both cases explain the different levels of fluctuating kinetic energy encountered close to the burner exit in Fig. 8. In a theoretical study [22], Juniper and Candel performed a stability analysis for the case of co-annular jets without swirl. They showed how stability is reduced if the inner stream mixes with the outer one before the exit plane of the outer tube, the same trend as reported here. It would be interesting to perform a similar stability analysis for cases with swirl.

Spectra. In the experiment [11], time signals of velocity have been recorded at several radial positions close to the burner exit at \( x/R = 0.1 \) for the case \( x_{\text{pilot}} = -0.73R \). The case \( x_{\text{pilot}} = 0 \) was not measured because in preliminary tests no instability was observed. During the simulation velocity and pressure signals were recorded at the same positions for a duration of 80\( t_h \). Furthermore, signals were recorded for each of these \( x \) and \( r \) positions at 12 different angular locations over which additional averaging was performed. On the symmetry axis no angular averaging is possible and only one signal was recorded, and at \( r/R = 0.1 \) and \( r/R = 0.18 \) only four angular signals were recorded with the particular grid used. The spectra were obtained splitting each signal in three overlapping segments of length 40\( t_h \), multiplying it by a Hanning window, and averaging over the segments.
The difference between the time signals of both cases is evident from Fig. 10. In the case $x_{\text{pilot}}=0$ (Fig. 10(a)), the signal exhibits the typical irregularity of a turbulent signal. Figure 10(b), on the other hand, shows that in the case $x_{\text{pilot}}=-0.73R$ a flow instability has developed that causes a regular oscillation of the signal with large amplitude. The low-frequency oscillations of this signal produce a pronounced peak in the power spectrum of the axial velocity fluctuations (Fig. 11). The frequency of the principal peak is $f_{\text{peak}}=0.25U_b/R$, which in dimensional units corresponds to a value of $f_{\text{peak}}=102$ Hz. The amplitude of the peak is very large, covering almost two decades in logarithmic scale. The total fluctuating energy is substantially larger than for the case $x_{\text{pilot}}=0$, reflected by the larger integral under this curve. This is in line with the fluctuating kinetic energy contours of Fig. 8 and the RMS values of Figs. 6 and 7. In the case $x_{\text{pilot}}=0$, no pronounced peak is observed, which confirms the preliminary experimental tests in which no flow instability was detected. The smaller peak, which appears in the case $x_{\text{pilot}}=0$ at a frequency $0.16U_b/R$, cannot be related to the small coherent structures observed in Fig. 9(c) because these structures have a shorter time scale, which would correspond to higher frequencies. This finding deserves further investigation.

A comparison of the spectrum from the LES for $x_{\text{pilot}}=-0.73R$ and the corresponding experimental spectrum in Fig. 11 serves to further validate the simulations. The agreement for both frequency and amplitude of the dominant peak is remarkable. Also the second harmonic is well predicted in the simulations.
The amplitude of the power spectrum at the peak frequency is now considered. It is quite a sensitive quantity, much more than the peak frequency itself. Figure 12 shows this amplitude at the fundamental frequency $f_{\text{peak}}$ as a function of the radial position. The shapes of the curves are different for the three velocity components. The simulation reproduces quite well the trends of the experiment. Only for $r/R<0.2$ the simulation overpredicts the amplitudes. In that region the impact of azimuthal averaging is small (even nonexistent at the axis) so that this could have an effect. In [9] similar plots were reported for an annular jet. It was shown there that an important issue is the location of the minimum for the amplitude of tangential velocity fluctuations. This minimum indicates the mean radial location of the center of the inner structure. Therefore, it is noteworthy that the minimum is well reproduced in the simulation.

### Conditionally Averaged Flow

It has been shown in the previous sections that large-scale structures rotating around the symmetry axis are present in the flow in the case $x_{\text{pilot}}=-0.73R$. Due to the high level of turbulence, the vortical structures are highly irregular as evidenced by the differences between Figs. 9(b) and 9(d). The pronounced peak in the power spectrum, Fig. 11, indicates that the rotation of the structure is very regular and allows the calculation of conditional averages. The purpose of the latter is to remove the irregularity induced by the turbulent motions. The method, which is described in the following section, consists basically in defining a coordinate system $y-z$ with origin at the symmetry axis, which rotates with the structure, and performing the averaging procedure in this rotating coordinate system. Note that it is not possible to perform this kind of analysis for the case $x_{\text{pilot}}=0$ due to a lack of a regular frequency of oscillation (Fig. 11).

**Procedure.** In order to investigate the main characteristics of the coherent structures, 140 instantaneous three-dimensional fields have been recorded. They are separated in time by $0.8t_b$, so that in each period of rotation of the structure five fields have been recorded. The time span covered by the fields is $112t_b$. If the oscillations are truly periodic, the definition of the axes which rotate with the structure is straightforward, with a fixed angle of rotation in a fixed time. In the present case, however, the motion of the structure is only quasi-periodic and therefore the method has to be more elaborate. The center of the structure has to be determined for each instantaneous field and a subsequent rotation of the field is performed, such that the center of the vortex is always on the $y$ axis. This is equivalent to defining a coordinate system $y-z$ that rotates with the structure.

The method is illustrated in Fig. 13 and proceeds as follows.

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![Figure 11: Power spectrum of axial velocity fluctuations at $x/R=0.1$, $r/R=0.73$. Solid line, experiment [11] $x_{\text{pilot}}=-0.73R$. Dashed line, simulation $x_{\text{pilot}}=-0.73R$. Dash-dotted line, simulation $x_{\text{pilot}}=0$.](image1)

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![Figure 12: Amplitude of the power spectrum at the fundamental frequency $f_{\text{peak}}$ at $x/R=0.1$ as a function of $r/R$ for case $x_{\text{pilot}}=-0.73R$. (a) Experiment [11]. (b) Simulation.](image2)
Determining the correlation between $u''$ and $p''$, it was found for that case that strong positive $u''$ values correlate with negative $p''$, i.e., the inner vortex structure, and, in fact, advance these in the sense of rotation. The same behavior is obvious in the present case from the conditional average. The surface of positive $u''$ fluctuations in Fig. 14(b) advances the negative $p''$ fluctuations of the inner structure in Fig. 14(a). When plotting all three iso-surfaces in a single graph it is even more visible that the downstream end of the positive $u''$-fluctuation surface winds along the connection line between the inner and the outer vortex structure of Fig. 14(a). This feeds the outer structure, turning in the clockwise sense around its own axis in the view of Fig. 14(a). Negative fluctuations of $u''$, represented by in Fig. 14(b), occur at the opposite side of the jet and seem not related to a continuously present rotating large-scale coherent structure.

Figures 15 and 16 show two-dimensional cuts of the conditionally averaged flow. Pseudo-streamlines of this flow field projected onto two planes are displayed. In Fig. 15 the pseudo-streamlines are based on $(u''_x, u''_z)$ and in Fig. 16 on $(u''_x, u''_r)$. The color represents $p''$ and the thick line indicates the contour line $u''_r=0$. The latter shows that the recirculation region is displaced off the symmetry axis in Fig. 15. The pressure minimum generated by the inner vortex structure is well visible in the $y-z$ plane together with the vortex motion surrounding it. The pressure minimum is off the axis at $r/R \approx 0.35$ (a posteriori justifying the choice of this radius for the conditioning) and by definition at the $y$ axis. The pseudo-streamlines spiral around a different point closer to the axis. The view in Fig. 15 is in the downstream direction and rotation of the flow and the structures is in the counter-clockwise direction. The recirculation region hence lags behind the inner structure by about 130 deg.

The inner and outer structures of Fig. 14 are also visible in Fig. 16. The inner structure shows up through the pressure minimum around $x/R=0$ and $z>0$. The outer structure is reflected by the recirculation regions and the spiralling or bending streamlines at the top and the bottom of the figure. From the pseudo-streamlines for $x \sim 0$ in this figure it is also clear that the inner structure is correlated with high forward axial velocity, for $z>0$, while the low axial velocity is located in the opposite side for $z<0$. This is indicated also by the asymmetry of the recirculation region (see also Fig. 17).

The previous information is contained in a more quantitative way in Fig. 17, which shows mean and conditional averaged profiles of pressure and velocity. In Fig. 17(a), the strength of the pressure minimum related to the center of the structure is visible by comparison to the mean pressure. Note also in Fig. 17(b) that the conditionally averaged axial velocity $u''_x$ at $y=0$, hence in the inner structure, is higher than the mean axial velocity. The recirculation zone, as expected from the two-dimensional plots, is displaced towards the opposite side. In Fig. 17(c), the radial position...
at which the conditionally averaged tangential velocity \( u^c_\theta \) at \( y = 0 \) equals the mean velocity roughly corresponds to the minimum of the pressure. This is also expected because at the center of the structure the fluctuations of the tangential velocity component have to vanish, as discussed in [9].

Finally, Fig. 18 shows the same plane as Fig. 15 but the color and streamlines are given by the equivalent Reynolds-decomposed quantities, i.e., color by \( p' - \langle p \rangle \) and streamlines by \( (u^c_r - \langle u^c_r \rangle, u^c_\theta - \langle u^c_\theta \rangle) \). The thick line again represents \( u^c_r = 0 \). In this figure the region of low pressure fluctuations corresponds to the inner structure of Fig. 14(a). Note that it forms outside the boundary of the recirculation zone.

Yazdabadi et al. [24] performed phase-averaged measurements in a cyclone dust separator and obtained similar plots as Fig. 15. Their conclusion was that the reverse flow zone displaces the central vortex core to create the precessing vortex core. The reverse flow zone would then provide feedback for the precessing vortex core and precess around the central axis behind the precessing vortex core. In the present case, Figs. 14(a) and 18 suggest an alternative explanation, although perhaps compatible with the previous one: The inner structure (precessing vortex core) is formed as an instability of the shear layer (Kelvin-Helmholtz instability). It is therefore formed on the boundary of the recirculation zone (Fig. 18) and advected by the mean flow. This structure then constrains the motion of the recirculation zone, which is displaced off the symmetry axis and precesses behind the structure.

Conclusions

Large-eddy simulations of incompressible flow in a swirl burner have been reported. The influence of geometrical features of the burner has been investigated by comparison of two cases with a different exit position of the inner jet. The simulations have...
been validated by comparison with corresponding experiments and very good agreement was obtained for mean flow, turbulent fluctuations, and the frequency of oscillation. The simulations have confirmed that the retraction of the pilot jet leads to the generation of enhanced flow instabilities. The related large-scale coherent structures have been identified and analyzed by using instantaneous plots, spectra, and conditional averages. The latter provides a precise picture of the characteristics of the large-scale coherent structures by removing the irregularity associated with the turbulent motions. These structures are relevant to the mixing of heat and species in the near field of the burner, and the technique can presumably be applied to the reactive case as well.

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Nomenclature

\[ f_{\text{peak}} \] = fundamental frequency of oscillation  
\[ k \] = fluctuating kinetic energy  
\[ p \] = modified pressure  
\[ R \] = outer radius of the main jet  
\[ \text{Re} \] = Reynolds number  
\[ \text{RMS} \] = root mean square  
\[ S \] = swirl number  
\[ t_p \] = characteristic time based on \( R \) and \( U_b \)  
\[ U_b \] = bulk velocity of the main jet  
\[ u_x \] = axial velocity component  
\[ u_y \] = radial velocity component  
\[ u_z \] = tangential velocity component  
\[ x, r, \theta \] = cylindrical coordinates (axial, radial, tangential)  
\[ x, y, z \] = Cartesian coordinates  
\[ x_{\text{pilot}} \] = axial location of the pilot jet exit  
\[ \alpha \] = angle used in the conditional-average technique  
\[ \langle \phi \rangle \] = mean value of the quantity \( \phi \)  
\[ \phi' \] = conditional average of the quantity \( \phi \)  
\[ \phi'' \] = instantaneous fluctuation of the quantity \( \phi \)  
\[ \rho \] = density

References


Fig. 18 Two-dimensional cut through the plane \( x/R \approx 0.1 \) of the conditional-averaged flow. Color is given by \( p_{\text{ruct}}(\rho) \). Pseudostreamlines calculated using \( u_x^2-\langle u_x \rangle \) and \( u_y^2-\langle u_y \rangle \). Thick black line \( u_z^2=0 \).