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Effect of boundary conditions on downstream vorticity from counter-rotating swirlers

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Abstract Particle image velocimetry (PIV) is utilized to measure the non-reacting flow field in a reflow combustor with multiple and single swirlers. The velocity field, vortex structure and total vorticity levels are experimentally obtained using two different boundary conditions, representing a single confined swirler and multiple swirlers in an annular combustor. The influence of the boundary conditions on the flow field at several locations downstream of the swirlers is experimentally investigated, showing that the central vortex in the multi-swirler case is more concentrated than in the single-swirler case. The vorticity of the central vortex and average cross-sectional vorticity are relatively low at the swirler outlet in both cases. Both of these statistics gradually increase to the maximum values near 20 mm downstream of the swirler outlet, and subsequently decrease. It is also found that the central vortex in the multi-swirler case is consistently greater than the single-swirler case. These results demonstrate the critical influence of boundary conditions on flow characteristic of swirling flow, providing insight into the difference of the experiments on test-bed combustor and the full-scale annular combustors.

1. Introduction

In aircraft engine combustors, a swirling flow is usually introduced to improve fuel mixing and flame stabilization aerodynamically. This swirling flow is established by introducing a tangential velocity to the main axial flow. When the swirl strength is greater than a critical value,[1] the rearward force induced by pressure gradient exceeds the forward aerodynamic force leading to a central recirculation zone. Central recirculation zone plays an important role in flame stabilization as it can return part of burned gas to the outlet of swirler to reduce the flow velocity of air at the outlet of swirler to local flame propagation speed, meanwhile its position and size directly affects the residence time of liquid fuel vapors, which has a great influence on the generation of NO_x.[2–4] Consequently, the swirler directly affects combustor performance. In this paper, the cold flow field downstream of a swirler was experimentally investigated using the particle image velocimetry (PIV) technique to provide reference data and elucidate the impact of boundary conditions on the behavior exhibited by a given swirler design.

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For the purposes of characterizing the flow field downstream of a swirler, PIV has several advantages over both traditional temperature- or pressure-based global measurements and other single-point laser diagnostic techniques such as laser Doppler velocimetry (LDV). In addition to its non-intrusive nature, PIV can provide a near-instantaneous view of a full 2D velocity field, without the directional ambiguity of Doppler-based measurement techniques. These advantages make it an excellent choice for providing both quantitative and qualitative insight into the nature of complicated flow fields.[5] Furthermore, the quantitative measurement of complete velocity field provides the possibility for the measurement of vorticity field.[6]

Due to the inherently 3D nature of swirling flow, the application of 2D PIV must be done with some care. In spite of the aforementioned complications, several studies have been completed to investigate the velocity vector field downstream of a single swirler. Reddy et al.[7] used PIV to investigate the non-reacting swirler flow field characteristics in a sudden expansion combustor. They obtained the variations in velocity, vorticity, Reynolds shearing stress, and turbulent intensity at various cross-sections downstream of the swirler and in the plane along the inlet flow direction, and analyzed the flow field characteristics of the central and corner recirculation zones. High levels of turbulence generated due to the swirling effect were noted in the study of Reddy et al.[7], and such turbulence in turn promotes rapid mixing. Kim et al.[8] utilized PIV to study downstream flowfield of swirler in a dump gas turbine combustor to provide new insights into the dynamics of turbulent swirl-stabilized flames, which are very important for the understanding of combustion instabilities. They observed that when combustion instability occurred, it was accompanied with the fluctuation of the recirculation zone. The fluctuation frequency of the recirculation zone was the same as the frequency of combustion instability. Gutmark et al.[9,10] systematically studied the relationship of vortex breakdown and combustion instability and they found that the source of combustion instability was associated with vortex breakdown. The research showed that vortex located at downstream of swirler had a significant relationship with combustion stability.

Bourgouin et al.[11] experimentally and numerically studied the impact of swirler structure on the central recirculation zone and the precessing vortex core (PVC) and they obtained that an increase in the swirler blade length could augment the maximum axial and azimuthal mean velocities downstream of the swirler and lead to an increase in the root mean square (RMS) velocity levels. With an increase in the swirl number, the central recirculation zone expanded in the transverse direction. The frequency of the PVC was also increased for the local rise of the mean azimuthal velocity. Moreover, the amplitude of the PVC was larger but vanished at a lower height in the combustion chamber.

Fureby et al.[12] and Grinstein et al.[2] experimentally and numerically investigated the non-reacting flow field of a single swirler in the free atmosphere and cylindrical flame tube using LDV, PIV, and flamelet-based large eddy simulation (LES). They obtained time-averaged velocity distributions and RMS turbulent velocities at several cross-sections downstream of the swirler. They obtained that in the confined domain case, the central recirculation zone was both longer and wider than in the open domain case. Fu et al.[13] investigated the impact of confinement on the downstream flow field of a counter-rotating swirler installed in eight square box test sections with different widths reporting that increasing the level of confinement increased the complexity of the flow field and had a significant influence on the mean and turbulent structure downstream from the swirler. Ceglia et al.[14] experimentally investigated the organization of the coherent structures arising within the near field of the swirling jet both in free and cylindrical confined configurations for water. They obtained that the confinement caused an increase of the swirl number and induced a larger spreading of the swirling jet promoting the enhancement of turbulence at the swirler exit.

Fanaca et al.[15] experimentally investigated and compared the flow fields of a 12-swirler annular combustor and a single swirler combustor. A free swirling jet flow was noted to form in the annular combustor, while a swirling wall jet flow regime existed in the single burner configuration. They proposed a new correlation, which allowed estimating the swirling jet flow regime for co-swirling burners in an annular combustion chamber. With this information, the single burner tests can be designed to match the annular combustor flow regime.

Boutazakhti et al.[16] utilized PIV and phase Doppler particle anemometry (PDPA) to map the velocity field downstream of a 3×3 square matrix of nine small swirlers, in addition to a single swirler configuration. The experimental results showed that in the merger region close to the swirlers, the characteristics of individual jets were still visible and the expansion rate of the central jet was slowed. In the developed region the cluster blended into a single jet-like flow with the axial component of the velocity field displaying self-similar properties.

Although the above investigations have characterized the flow field downstream of the swirlers in some burners in detail, no open literature has been published to quantitatively investigate the influence of varied boundary conditions on the velocity field and vortex structure along the flow direction for a fixed swirler configuration. Because the vortex structure has significant effects on the combustion performance of the burner,[1] it is critical to understand how the imposition of various boundary conditions changes the overall vortex structure of a given swirler. The current work aims to highlight and quantify this impact with a simplified combustor geometry using PIV measurements to obtain the vorticity fields at several locations downstream of the swirler.

2. Experimental apparatus

2.1. Combustor configuration

To study the effect of boundary conditions on the vertical structures evolved from a given swirler, a three swirler combustor was designed, as shown in Fig. 1. Using this configuration, two different sets of boundary conditions can be studied. The first, utilizing all three swirlers, is similar in nature to the conditions found in an annular combustor where individual swirlers are allowed to interact. In this configuration, the section downstream of the central swirler is the region of interest, with the upper and lower boundary conditions being solid walls, as well as periodic free boundary conditions present at the left and right boundaries. The second configuration consists of a single swirler surrounded on each side by a solid wall. This condition is achieved by placing a solid boundary between Swirlers 1 and 2, isolating Swirler 2. These two cases are referred to hereafter as multi-swirler and single-swirler, respectively.