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Technical Notes

Vortical Structure of Reacting Flow in a Sudden-Expansion Combustor with Solid Fuel

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Nomenclature

h = step height
T_0 = temperature of the oxidizing stream
U_0 = centerline velocity of the oxidizing stream
U_1 = upper stream velocity of the mixing layer
U_2 = lower stream velocity of the mixing layer
u = x component of velocity
$-u'v'$ = Reynolds stress
v = $y$component of velocity
Xr = reattachment length
x = streamwise direction
y = wall-normal direction
δ_ω = vorticity thickness

I. Introduction

BACKSTEPS are widely adopted as flame holders, and the corresponding flow possesses direct impact on combustor performance. Among the flow patterns involved, the characteristic of the shear layer is critical. For either a reacting or nonreacting case, the shear layer is dominated by large coherent structures [1,2] that function as mixers through strong turbulent diffusion [3]. Nonetheless, the reacting shear layer possesses a smaller rate of spreading, along which eddies accelerate downstream with increased size and spacing. Although more investigations focus on premixed combustion within sudden-expansion combustors [1,2,4], fewer are reported for the nonpremixed case involving solid fuel [5,6], which has significant potential for propulsion applications. In this work, vortical structures of nonpremixed reacting flow within a sudden-expansion combustor are investigated experimentally. The reacting flow is made available by pygoren ignition of the polymethylmethacrylate (PMMA) slab.

II. Experiment Setup

Figure 1 shows the connected-pipe test facility for this work. The test section is a sudden-expansion combustor ($h = 35$ mm) with optical access except the bottom wall. A thermocouple port positioned 140 mm upstream of the back step monitors the temperature of the oxidizing stream ($T_0 = 810°\mathrm{C}$, $[\mathrm{O_2}] \sim 11.3\%$). Once the prescribed T_0 is attained, the fuel (PMMA, thickness 6 mm) is inserted into the combustor through a gate downstream.

High-speed photography (1000 fps) is used for flow visualization, whereas particle-image velocimetry (New Wave Solo 120 Nd:YAG laser at 15 Hz) is adopted for quantitative analysis with an interrogation region of 16×16 pixels. The oxidizing stream is seeded with $\mathrm{Al_2O_3}$ particles (average diameter: 3 μm). Two overlapping laser sheets are intersected along the central axis of the combustor and sequentially pulsed with a 300 μs delay. According to Richard and Donald [7], the uncertainty of the measured velocity is $\pm 3.2\%$ (at 95% confidence level).

III. Results and Discussion

A. Transient Vortical Structures

To reveal the vortical structure of the reacting flow within the combustor, the nonreacting case is demonstrated first as the basis for comparison. Small eddies are spread downstream while forming into larger coherent structures (Fig. 2), which is attributed to the flapping shear layer and the potential of vortex pairing [8]. However, due to the reattachment of the shear layer, the pairing potential is decreased through momentum dissipation. Consequently, the small eddies engulfed within the coherent structures are released and scattered further downstream.

For the nonpremixed reacting case, the proceeding combustion introduces large vortical structures along the heated oxidizing stream (Fig. 3). The mixing between the oxidizing stream and fuel vapor is assisted by the large vortices, which is verified by the distinct distributions of seeding particles. Small eddies are absent within the reacting shear layer due to the heat release [1]. Nonetheless, the pattern of large vortices is distinct from that revealed in the premixed case [1], which is similar to that in the nonreacting flow. The phenomenon is attributed to the diffusion-controlled and distributed heat release, which is typical of the nonpremixed combustion of solid fuel [5].

B. Averaged Vortical Structures

Figure 4 demonstrates the streamline contours averaged over 450 data. For the nonreacting flow, a large recirculation structure locates downstream of the back step with a reattachment length (Xr) of 7 h. Under combustion, the recirculation is significantly weakened, and a 30% decrease in Xr is observed, which is similar to the premixed case [2].

The concept of vorticity thickness (δ_ω) [2] is introduced to evaluate the difference between the mixing layers in nonreacting and reacting flows. It is defined as

$$\delta_w = \Delta U \Big/ \left(\frac{\partial u}{\partial y}\right)\Bigg|_{\max} \tag{1}$$

in which $\Delta U = U_1 - U_2$. U_1 and U_2 are the upper and lower stream velocities of the mixing layer, respectively. The uncertainty of δ_ω is $\pm 4.3\%$.

An approximately linear increase in δ_ω (slope ≈ 3.1) is demonstrated for the nonreacting flow upstream of the streamwise location $x/h = 8$ (Fig. 5), whereas the decrease in δ_ω immediately downstream implies the breaking of large vortices upon reattachment. The released

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