JOURNAL OF PROPULSION AND POWER
Vol. 25, No. 5, September–October 2009

Technical Notes

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

F. C. Hsiao*
National Tsing Hua University, Hsinchu, 30013, Taiwan, Republic of China
and
Y. H. Lai* and J. T. Yang‡
National Taiwan University, Taipei, 10617, Taiwan, Republic of China

DOI: 10.2514/1.41914

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.

Received 30 October 2008; revision received 9 April 2009; accepted for publication 19 May 2009.

*Ph.D. Candidate, Department of Power Mechanical Engineering; d937706@oz.nthu.edu.tw.

†Postdoctoral Associate, Department of Mechanical Engineering; yhlai1125@gmail.com.

‡Professor, Department of Mechanical Engineering; jtyang@ntu.edu.tw.

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 ($T_0 = 810°C$, $[O_2] \sim 11.3\%$). 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 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

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

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

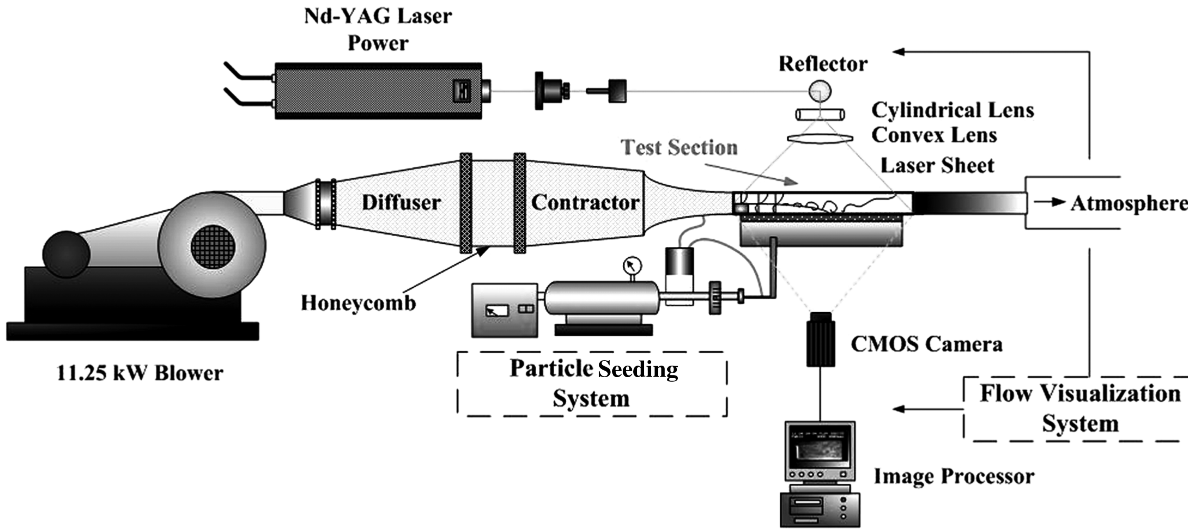

Fig. 1 Schematic drawing of the connected-pipe test facility.

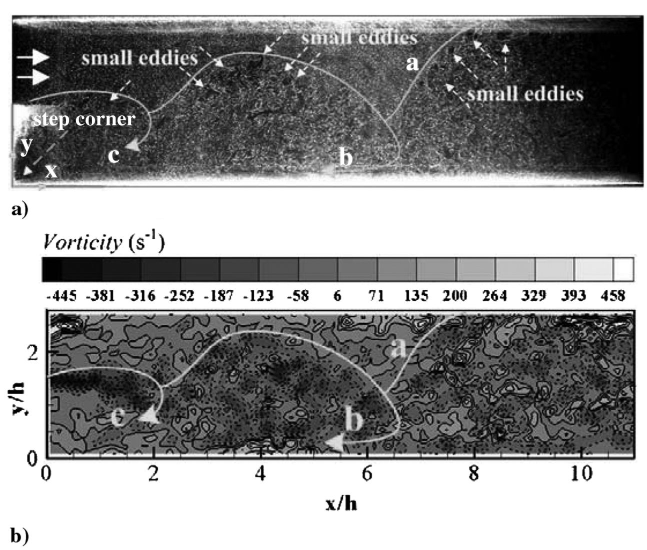

Fig. 2 Transient nonreacting flow: a) flow structure, and b) vorticity contours.

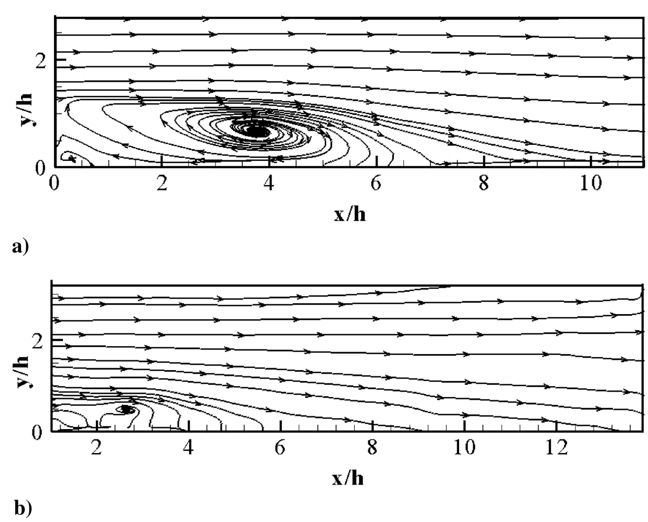

Fig. 4 Averaged streamline contours: a) nonreacting flow, and b) reacting flow.

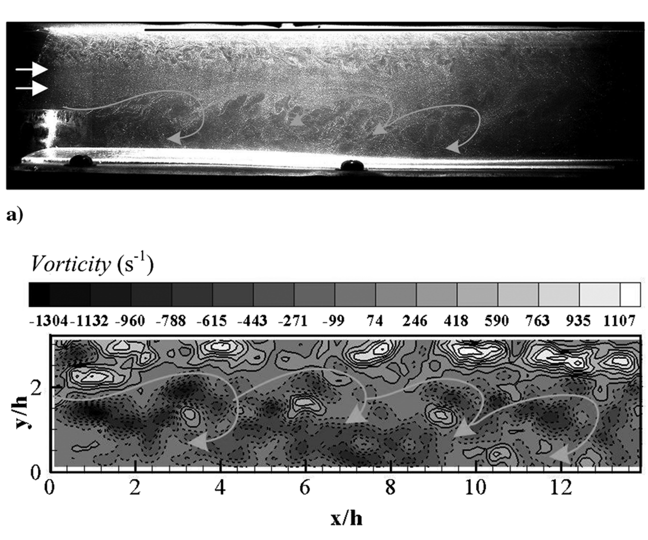

Fig. 3 Transient reacting flow: a) flow structure, and b) vorticity contours.

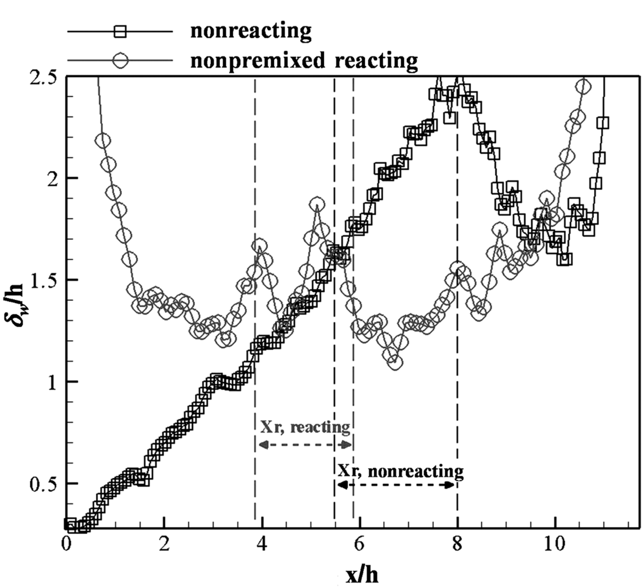

Fig. 5 Vorticity thickness of the shear layer.

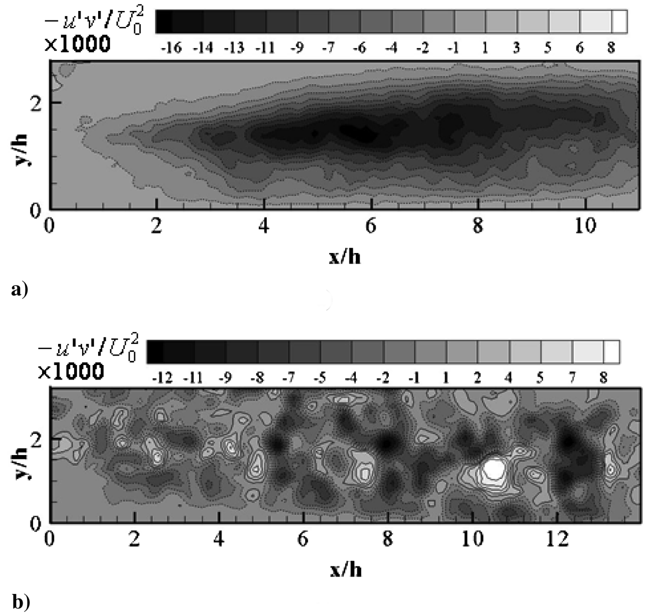

Fig. 6 Distributions of normalized Reynolds stress: a) nonreacting flow, and b) reacting flow.

small eddies are then revealed by the increase in δ_ω downstream of $x/h = 10$.

On the contrary, the decrease in δ_ω upstream of $x/h = 1$ indicates the lag of shear layer formation in the nonpremixed reacting flow. The δ_ω for the reacting case is significantly larger compared to its nonreacting counterpart, which is attributed to the dilatation effect. A slight decrease in δ_ω (slope ≈ -0.1) is observed downstream, while it fluctuates around the reattachment region ($x/h = 3.9 \sim 5.9$). Because the diffusion flame is distributed along the shear layer, the increased velocity gradient ($\partial u/\partial y|_{\max}$) introduced by the intense reaction decreases the δ_ω. The intense fluctuation in δ_ω downstream of the reattachment region again indicates the breaking of large vortices.

Distinct distributions of the Reynolds stress in nonreacting and reacting cases are revealed in Fig. 6. A clear contour of the shear layer is observed in the nonreacting flow, in which the most intense stress locates around the center. Nonetheless, the distributions of the Reynolds stress and vorticity are not consistent, which implies the limited contribution by small eddies to mixing within the streamwise section $x = 4 \sim 8$ h. Contrarily, the contour of the Reynolds stress in the reacting flow is fluctuating. The situation is consistent with that of the vorticity and indicates the major contribution to mixing by the interactions among large vortical structures.

IV. Conclusions

This study investigates the vortical structure of nonpremixed combustion of solid fuel in a sudden-expansion combustor, which rarely been studied or discussed in the past. The mixing and combustion are dominated by the large-scale vortical structures, which are also affected by the dilatation effect introduced by reaction. Although the vortical structures in nonreacting flow resemble those in the premixed reacting case, a distinct pattern of vortices is observed for the nonpremixed reacting flow. The uniqueness is attributed to the distributed heat release typical of solid fuel combustion. Although small eddies merge into large-scale coherent structures in the nonreacting flow, they are essentially diminished in the nonpremixed reacting case, which is dominated only by large coherent vortices. Because of the existence of diffusion flame along the shear layer, intense interactions are observed among the vortices, which also enhanced the mixing between the oxidizing stream and fuel vapor. A linear increase in the vorticity thickness (slope ≈ 3.1) is observed upstream of the reattachment ($x/h \sim 7$) in the nonreacting case, whereas a large initial value with a slight decrease (slope ≈ -0.1) is revealed for the nonpremixed reacting flow upstream of the reattachment ($x/h \sim 5$). The results may benefit the understanding and advancement of propulsion systems with solid fuel.

References

[1] Ganji, A. R., and Sawyer, R. F., "Experimental Study of the Flow Field of a Two-Dimensional Premixed Turbulent Flame," *AIAA Journal*, Vol. 18, 1980, pp. 817–824.
doi:10.2514/3.50823

[2] Pitz, R. W., and Daily, J. W., "Combustion in a Turbulent Mixing Layer Formed at a Rearward-Facing Step," *AIAA Journal*, Vol. 21, No. 11, 1983, pp. 1565–1570.
doi:10.2514/3.8290

[3] Ahmed, S. A., and Abidogun, K. B., "Measurements of Turbulence Statistics and Energy Budgets in a Model Combustor," *Energy*, Vol. 23, No. 9, 1998, pp. 741–752.
doi:10.1016/S0360-5442(97)00077-7

[4] Altay, H. M., Speth, R. L., Hudgins, D. E., and Ghoniem, A. F., "Flame-Vortex Interaction Driven Combustion Dynamics in a Backward-Facing Step Combustor," *Combustion and Flame*, Vol. 156, 2009, pp. 1111–1125.
doi:10.1016/j.combustflame.2009.02.003

[5] Krishnan, S., and George, P., "Solid Fuel Ramjet Combustor Design," *Progress in Aerospace Sciences*, Vol. 34, 1998, pp. 219–256.
doi:10.1016/S0376-0421(98)00005-0

[6] Yang, J. T., and Wu, C. Y. Y., "Controlling Mechanisms of Ignition of Solid Fuel in a Sudden-Expansion Combustor," *Journal of Propulsion and Power*, Vol. 11, No. 3, 1995, pp. 483–488.
doi:10.2514/3.23868

[7] Richard, S. F., and Donald, E. B., *Theory and Design for Mechanical Measurements*, Wiley, New York, 1995.

[8] Winant, C. D., and Browand, F. K., "Vortex Pairing: The Mechanism of Turbulent Mixing-Layer Growth at Moderate Reynolds Number," *Journal of Fluid Mechanics*, Vol. 63, 1974, pp. 237–255.
doi:10.1017/S0022112074001121

C. Segal
Associate Editor