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Thermal characteristics and exhaust-gas analysis behind bluff-body frustums

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HIGHLIGHTS

- Four configurations of frustums were used to modulate the flow momentum.
- The lifted flame is dismissed behind the bluff-body frustums.
- The high *T.I.* caused from the bluff-body and rifled effects generates high mixing between air and fuel.
- The high mixing air–fuel combustion corresponds to the high total combustion intensity and low C_{NO}.

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ABSTRACT

Four configurations of frustums (unrifled, inner-rifled, outer-rifled and two-faced rifled) were used to modulate the flow momentum. The rifle configuration transformed the axial flow velocity to radial direction for increasing the turbulence intensity (*T.I.*). The increased *T.I.* improved the mixing between the air and fuel flow. Direct photography, Schlieren photography, hot-wire anemometry, thermocouple, and gas analyzer were utilized to measure the flame length, turbulence intensity, flame temperature, heat release, and exhaust-gas concentrations. The Schlieren flame structures show that the lifted flame is dismissed behind the unrifled, inner-rifled, outer-rifled, and two-faced rifled frustums; and therefore, the flame can be further stabilized. Behind the two-faced rifled frustum, the *T.I.* increased from 0.15% to 4.6% and the non-dimensional flame length (H/D) decreased from 24 to 14 (*i.e.*, a flame shortening of around 42%). The low flame temperature approximately corresponded to the low concentration of nitride oxide (C_{NO}). The high air–fuel mixing (caused by the high *T.I.*) corresponded to a high total combustion intensity and a low NO.

1. Introduction

The exhausted products that results from various energy resources pollutes the natural environment. Many governments worldwide are exploring new alternative energy sources or adopting high-efficiency combustors to save energy and reduce carbon emissions. In traditional industries, the swirl-jet flow and bluff-body effects were applied to improve the heat conduction and combustion ability. These two effects were used in boilers, gas-turbine engines, and gas stoves. As air flows around the bluff body, the inverse pressure gradient generates a local low-pressure recirculation zone behind the bluff body. In this recirculation zone, the air and fuel flows are adjustable and the flame fields are stable. In addition, the diffusion between the flow and recirculation flow increases the turbulence intensity (*T.I.*) and extends the retention time. The increased *T.I.* intensifies the mixing of air and fuel, promotes the heat release, and improves the flame stability. The flame lifted and blow-off are excluded due to the improved flame stability.

Many researches studied the jet diffusion flames. The diffusion flame utilized a high speed to drive a strong convection effect. This convection effect blow the fuel out from the nozzle exit and form a fuel jet. The fuel particles diffuse outward and the outer co-annular airflow diffuse inward due to the entrainment effect. Then, these two jets are ignited and triggered the chemical combustion reaction (i.e., the jet diffusion flame). Consequently, the jet diffusion flame contains both the particle diffusion behavior and flow convection. Sze et al. [1] experimentally investigated the appearance, temperature distribution, and NOx emission index of two inverse

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Nomenclature

A_a	exit area of annular jet: $\pi({D_o}^2 - D^2)/4$, 392.7 mm^2
A_c	exit area of central jet: $\pi d^2/4$, 19.6 mm^2
D	outer diameter of sleeve, 20 mm
D_i	top diameter of frustum, 15 mm
D_h	hydraulic diameter of annular jet at exit: $D_o - D$, 10 mm
D_o	outer diameter of annular jet at exit, 30 mm
d	exit diameter of central jet, 5 mm
H	flame length, cm
Q_{tot}	total combustion intensity
r	radial coordinate, originated at center of bluff-body frustums
T	flame temperature, K
$T.I.$	turbulence intensity near the frustum exit at $(x/D, r/D) = (0.2, 0)\left(= \frac{\sqrt{(u'^2+v'^2)/2}}{\sqrt{u_c^2+u_a^2}}\right)$
$T_{\max}$	highest central flame temperature along the central axis, K
u	axial velocity
u_a	volumetric mean axial velocity of annular air-jet at exit: ϕ_a/A_a
u_c	volumetric mean velocity of central fuel-jet at exit: ϕ_c/A_c
v	radial velocity
x	axial coordinate, originated at center of bluff-body frustums
ν_a	kinematic viscosity of air
ν_f	kinematic viscosity of fuel
ϕ_a	volumetric flow rate of annular air-jet
ϕ_c	volumetric flow rate of central fuel-jet

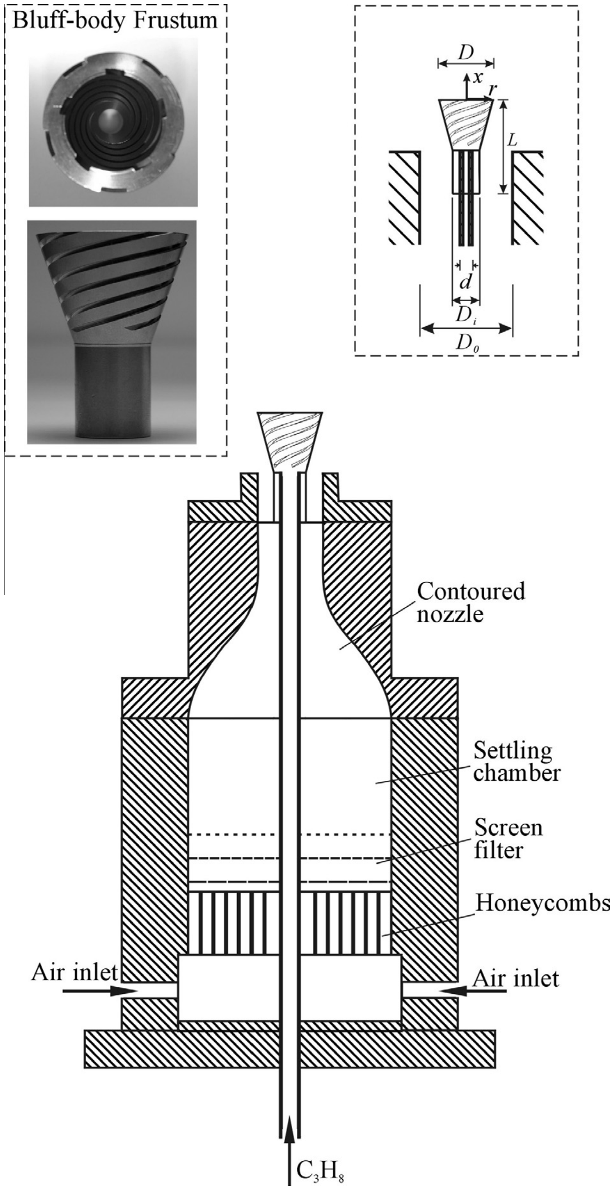

Fig. 1. Experimental setup utilized in San et al. [10,11].

diffusion flames—circumferentially arranged ports (CAPs) and co-axial (CoA) jets. The flame temperature in the CAP flame was higher than that in the CoA flame at higher overall equivalence ratios (Φ_s). The centerline oxygen concentrations showed that the air–fuel mixing in the CAP flame was more intense than that in CoA flame. The emission index of NOx (EI_{NOx}) for both flames at Re = 2500 revealed a maximum EI_{NOx} of 3.2 g/kg at $\Phi = 1.2$ for CAP flame and 3 g/kg at $\Phi = 2.2$ for CoA flame. Lee et al. [2] utilized light scattering photography to visualize the effects of forced amplitude in tone-excited jet diffusion flames. Flame behavior is classified as jet-diffusion, fat, elongated, and in-burning flames. Elongated flames exhibit a turnabout phenomenon of vortex motion and a reversed vortex roll-up direction. The evolution process of the inner flow structure directly influences flame length. The negative acoustic cycle dramatically changes the shapes of the fuel stem, fuel branch, and direction of vortex roll up. Xu and Yan [3] numerically studied the flicker frequency of a combustion flame by using a wavelet-based prefiltering of the original flame signal and an adaptive truncation of the spectrum of the filtered signal. They discovered that wavelet filtering largely deleted white noise. Gollahalli et al. [4] investigated the flame structures and hystereses by using contoured nozzles. They utilized Schlieren photography to visualize the near-field of nozzle of cold flow, attached flame, lifted flame, and attached to lifted flame transition. The mean celebrities and Strouhal numbers were 0.94 and 2.8 for the lifted flame, respectively; and those of 0.62 and 1.30 for the reattached flame, respectively. They also demonstrated that molecular diffusion dominated the lifting process and that the dynamics of the organized structures controlled the reattachment process. The differences between the flame-based structures in the lift and reattachment configurations dominated the hysteresis phenomenon. Wu et al. [5] experimentally studied the complicated flame stabilization mechanisms and flame/flow interactions in the blowout of non-premixed turbulent jet flames. They classified the blowout process as four characteristic patterns: pulsating, onset of receding, receding, and extinction. They also demonstrated that the maximum waistline point separated the unstable and stable regions in the blowout process for the lifted flame. The flame properties are different with comparing jet diffusion flames and pre-mixed flames. The diffusion flame swings and is longer than that of pre-mixed flame. The flame color is yellow, unlike that of blue for the pre-mixed flame. The heat radiation in diffusion flame is stronger that that in pre-mixed flame. The flame behaviors include the lifted, blow-off and drop-back in diffusion flame. The hydrocarbon and soot produced from incomplete combustion in diffusion flame is more than those in pre-mixed flame.