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Characteristics of backward-inclined non-premixed jet flames in crossflow

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ABSTRACT

The characteristics of backward-inclined non-premixed jet flames in a uniform crossflow were studied in a wind tunnel. Time-averaged photography techniques were used to study flame behavior. The flow field was captured by short exposure photography and Mie-scattering techniques. Flame temperatures were probed with a fine-wire R-type thermocouple. In the domain of jet-to-crossflow momentum flux ratio R and backward-inclination angle θ, the flames were categorized into three characteristic modes. The first mode consisted of *crossflow dominated flames* characterized by a down-wash recirculation flame in the wake of the burner tube. The second mode consisted of *transitional flames* characterized by a yellowish recirculation flame and a tail flame. The third mode consisted of *jet dominated flames* characterized by a blue flame base and an absence of the down-wash flame. The down-wash recirculation flames were observed for a backward inclination angle of $\theta < 40^\circ$. The ability of the flames to resist blow off when increasing the jet-to-crossflow momentum flux ratio decreased as θ increased. Coherent vortices were observed on the seeded fuel jet, whose type was dependent on R and θ. In the upstream region, the fuel appeared above the flame. However, in the downstream region, the fuel became engulfed within the flame. For a fixed θ, the Strouhal number of the upwind shear layer vortices on the fuel jet was observed to decrease asymptotically as R increased. In the near-field at $x/d \approx 5$, the *crossflow dominated flames* presented temperature profiles characterized by a broad dual-hump peak profile in the symmetry plane, while in the near-field at $x/d \approx 5$, the *jet dominated flames* presented a single peak profile in the symmetry plane.

1. Introduction

Jet flames in crossflow have been investigated due to their wide range of practical applications. Some common applications include gas turbine combustors, industrial burners, and gas flaring during the disposal of unwanted flammable gases. Some of the applications require the fuel jet to be injected into the crossflow from an orifice on the wall. This condition is called a wall-issued jet flame in crossflow. Under this condition, the issuing fuel jet is subjected to the influences of the crossflow and the wall boundary layer. A number of studies on wall-issued jet flames in crossflow [1–7] have reported on flame behaviors, stability, thermal-chemical structure, jet trajectory, etc. Other applications required the fuel jet to be injected into the crossflow through a stack or a tube that penetrates through the wall and protrudes it. Such flames have been classified as stack-issued jet flames in crossflow [8–26]. These flames are influenced by the aerodynamic interactions of the fuel jet, the crossflow, and the elevated stack.

Depending on the jet-to-crossflow momentum flux ratio R, stack-issued jet flames in crossflow can be classified as lifted jet flames in crossflow or wake-stabilized jet flames in crossflow [21]. At a jet-to-crossflow momentum flux ratio R above a given critical value, the flames are lifted and stabilized on the lee-side of the bent jet. These flames are characterized by a kidney-shaped, counter-rotating vortex pair [11,15,27]. The kidney-shaped, counter-rotating vortex pair has also been reported in non-reacting jets in crossflow at a high jet-to-crossflow momentum flux ratio R [28–33]. The counter-rotating vortex pair originates in the upstream of the fuel jet and grows in strength toward the zone of developed flow in the downstream region. The counter-rotating vortex pair makes the jets in crossflow superior mixers when compared to free jets or jets in co-flowing airstreams. The wake-stabilized jet flames are characterized by the recirculation zone behind the burner tube and the wake vortices shed by the burner tube. The recirculation zone makes the wake-stabilized flame resist blow off, and the flames can then exist at high crossflow velocities compared to their lifted flames counterparts. Some researchers [16–19,21,24,34,35] have investigated the stability characteristics, flame lengths, thermal-chemical structures, acoustic excitations, and scaling laws for predicting the shape and size of the wake-stabilized jet flames in crossflow. The

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Nomenclature

D	outer diameter of burner tube, 6.4 mm
d	inner diameter of burner tube, 5.0 mm
f	instability frequency of upwind-side shear layer vortices, Hz
L	length of burner tube, 510 mm
l_{bf}	blue flame length, mm
l_{tf}	total visible flame length, mm
R	jet-to-crossflow momentum flux ratio ($=\rho_j u_j^2/\rho_w u_w^2$)
Re_j	jet Reynolds number ($=u_j d/\nu_j$)
Re_w	crossflow Reynolds number ($=u_w D/\nu_w$)
St	strouhal number ($=fd/u_j$)
T	time-averaged flame temperature, °C
u_j	average jet velocity at exit of burner tube ($4Q_j/\pi d^2$), m/s
u_w	crossflow velocity, m/s
W_{rf}	recirculation flame length, mm
x	Cartesian coordinate in axial direction
y	Cartesian coordinate in cross-stream direction
z	vertical coordinate
θ	backward inclination angle of burner tube evaluated from the direction normal to the crossflow
ρ_j	fuel jet density, kg/m^3
ρ_w	density of crossflow air, kg/m^3
ν_j	kinematic viscosity of fuel jet, m^2/s
ν_j	kinematic viscosity of crossflow air, m^2/s
%	percentage

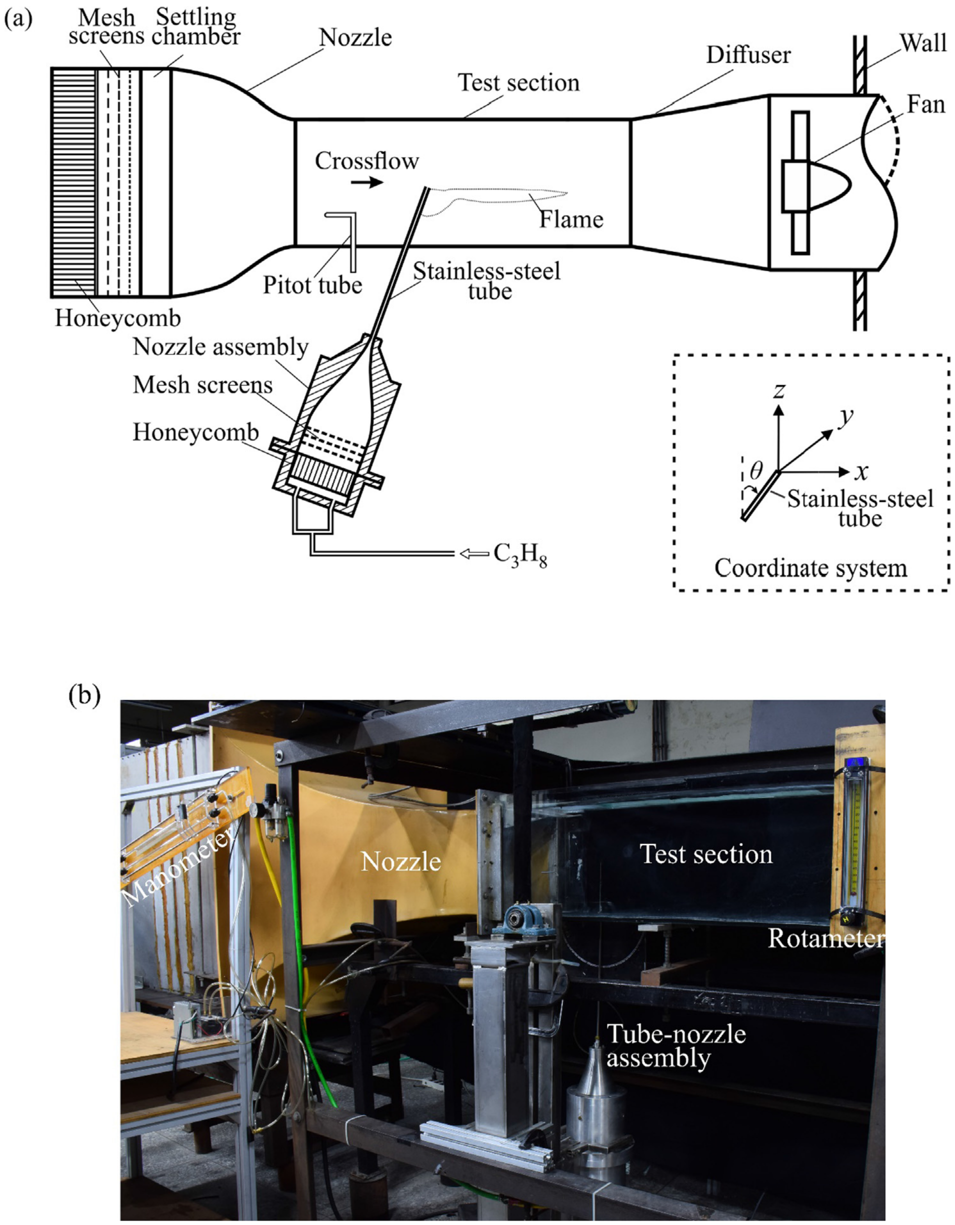

Fig. 1. Experimental setup.