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Blow-out limits of nonpremixed turbulent jet flames in a cross flow at atmospheric and sub-atmospheric pressures

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ABSTRACT

The blow-out limits of nonpremixed turbulent jet flames in cross flows were studied, especially concerning the effect of ambient pressure, by conducting experiments at atmospheric and sub-atmospheric pressures. The combined effects of air flow and pressure were investigated by a series of experiments conducted in an especially built wind tunnel in Lhasa, a city on the Tibetan plateau where the altitude is 3650 m and the atmospheric pressure condition is naturally low (64 kPa). These results were compared with results obtained from a wind tunnel at standard atmospheric pressure (100 kPa) in Hefei city (altitude 50 m). The size of the fuel nozzles used in the experiments ranged from 3 to 8 mm in diameter and propane was used as the fuel. It was found that the blow-out limit of the air speed of the cross flow first increased ("cross flow dominant" regime) and then decreased ("fuel jet dominant" regime) as the fuel jet velocity increased in both pressures; however, the blow-out limit of the air speed of the cross flow was much lower at sub-atmospheric pressure than that at standard atmospheric pressure whereas the domain of the blow-out limit curve (in a plot of the air speed of the cross flow versus the fuel jet velocity) shrank as the pressure decreased. A theoretical model was developed to characterize the blow-out limit of nonpremixed jet flames in a cross flow based on a Damköhler number, defined as the ratio between the mixing time and the characteristic reaction time. A satisfactory correlation was obtained at relative strong cross flow conditions ("cross flow dominant" regime) that included the effects of the air speed of the cross flow, fuel jet velocity, nozzle diameter and pressure.

1. Introduction

Flame stabilization of nonpremixed turbulent jet flames has been studied extensively because of the fundamental importance of understanding physical mechanisms as well as because of the importance of flame stabilization to burner design. Lift-off heights and blow-out limits are important parameters in characterizing nonpremixed jet flame stability. Even under quiescent air conditions [1], the stabilization and blow-out is quite complex. Much research has been conducted to interpret this behavior with several controlling mechanisms proposed [2–5]. Kalghatgi [5] developed a premixed flame model and successfully quantified the blow-out limit of gaseous jet diffusion flames in quiescent air with a universal non-dimensional formula. Broadwell et al. [4] proposed a large-scale mixing model and defined as a criterion of the ratio between the chemical reaction time and the turbulent mixing time to characterize the stability of turbulent diffusion flames. The effect of coflow air on the blow-out limit was also investigated [6–15] and an effective velocity was proposed. The effect of coflow air temperature was also studied [16,17].

In contrast, although the flame stabilization of nonpremixed jet flames in cross flows is practically important to combustor burners [18] as well as to flares employed for emergency venting and gas separation of petrochemical and refinery stacks [19], studies of the blow-out limit in cross flows are rather limited. Any cross flow makes the flame stabilization of nonpremixed jet flames much more complicated by influencing turbulent mixing. As a consequence, quantifying flame stabilization of nonpremixed jet flames in cross flow is very difficult. Previously, Kalghatgi [20] proposed a widely applied empirical blow-out limit curve (u_∞/D versus u_e/D), where u_∞ and u_e are the velocities of the cross air flow and fuel jet, respectively, and D is the nozzle diameter. The blow-out phenomenon was further discussed by Lee and Shin [21] and direct numerical simulations (DNS) of flame stabilization and blow-out in a nitrogen-diluted hydrogen transverse jet were conducted by Chen and coworkers [22–24]. However, a

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Nomenclature

D	inner nozzle diameter (mm)
Da	Damköhler number
L_{cr}	critical length of flame lift-off trajectory line at blow-out (m)
P_∞	ambient pressure (kPa)
R	momentum ratio of fuel flow to cross flow
s	the arch length of trajectory line (m)
S_L	laminar flame speed (m/s)
T	temperature (K)
u_c	local centerline velocity (m/s)
$\tilde{u}_c$	effective velocity for flame in cross flow (m/s)
u_{co}	coflow velocity (m/s)
$u_{c,x}$	local centerline velocity in cross direction (m/s)
$u_{c,y}$	local centerline velocity in jet direction (m/s)
u_e	velocity of fuel ejected from nozzle (m/s)
u_{eff}	effective velocity for coflow flame (m/s)
u_∞	velocity of cross flow (m/s)
x_{cr}	critical distance in cross direction of flame lift-off trajectory line at blow-out (m)

Greek symbols

δ	local flame diameter
α	thermal diffusivity (m^2/s)
ρ_e	fuel density (kg/m^3)
ρ_∞	ambient air density (kg/m^3)
ρ_{co}	coflow air density (kg/m^3)
θ	angle between flame body and jet direction
τ_m	mixing time in Eq. (1)
τ_c	chemical reaction time in Eq. (1)

Subscripts

∞	ambient
e	fuel

theoretical model is still needed to describe the blow-out limits of nonpremixed turbulent jet flames in cross flows.

Concerning the pressure effect, there has been no published study on blow-out limits with cross flows especially at the sub-atmospheric pressure condition, although such a condition is realistic, for example, at high-altitude locations. Recently, several experiments [25–27] were carried out in Lhasa, a city on the Tibetan plateau (altitude 3650 m; pressure 64 kPa). Combustion behaviors, including lift-off [27], at this sub-atmospheric pressure were found to differ appreciably from those at standard atmospheric pressure (100 kPa). The blow-out limits with cross flows at sub-atmospheric pressure are important and crucial to the design and use of diffusion jet burners and flares in high altitude regions.

In this study, experiments were carried out using an especially built wind tunnel in Lhasa where the atmospheric pressure is naturally low (64 kPa). Results from these experiments were compared with those from a wind tunnel in Hefei, where the atmospheric pressure is standard (100 kPa), to evaluate the effect of pressure on blow-out limits in cross flows. A theoretical model was also developed to interpret blow-out limit behaviors when the air speed of the cross flow as well as the ambient pressure were varied.

2. Experiment

A wind tunnel was built in Lhasa, Tibet (altitude 3650 m) where the ambient pressure is $P_\infty = 64$ kPa. The cross-section of the wind tunnel is 1.5 m in height and 1.2 m in width and its length is 10 m, as schematically shown in Fig. 1. In the tunnel, the cross air flow is generated by a mechanical fan installed at one end. A honeycomb

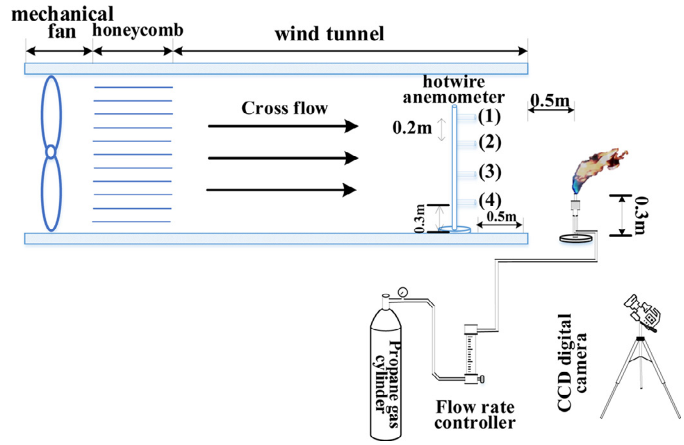

Fig. 1. Schematic of the experimental setup.

is also installed in the tunnel for flow stabilization. The other end of the tunnel is open. The velocity profile at the outlet of the wind tunnel (monitored by a four-probe anemometer), as well as that applied to the flame, is measured to be uniform having turbulence statistical values of u_{rms}/u_{mean} less than 2%. Fuel jet nozzles with the inner diameters of 3–8 mm and wall thicknesses of about 1.5 mm were placed 0.5 m from the exit of the wind tunnel. The fuel nozzle exit was located 0.3 m above the bottom level of the wind tunnel. The fuel was propane and the flow rate was regulated by a gas flow rate meter. Corresponding experiments under normal atmospheric pressure were conducted in a wind tunnel in Hefei (altitude 50 m; $P_\infty = 100$ kPa). The details of this wind tunnel were described previously [28]. The ambient temperature is around 291 K in Lhasa and 293 K in Hefei, respectively; the fuel temperature at the outlet of the nozzle was measured to be the same as the temperature of the environment. The flames were recorded by a CCD camera. All experiments were repeated three times.

3. Results and discussion

3.1. Flame evolution and blow-out limit

Figure 2 shows photos of the nonpremixed turbulent jet flames that exhibit typical variations in shape when subjected to cross flows with increasing air speed, u_∞. At a fixed fuel jet velocity of $u_e = 39.3$ m/s for $D = 3$ mm and $P_\infty = 100$ kPa (a), the flame is lifted even without the cross flow with a lift-off height of 7.2 cm. This lifted flame behavior with cross flow is therefore different in nature from a "wake-stabilized flame" [29] in which the flame is stabilized in the near-nozzle wake region when the momentum ratio of the fuel jet to the air stream is small.

The result shows that there are three regimes depending on the air speed. For u_∞, up to ~2.0 m/s, the degree of bending of the flame becomes more pronounced with increasing air speed. Simultaneously, the flame height and length decrease and the blue flame region enlarges. This can be attributed to enhanced air entrainment and mixing into the fuel region with u_∞ in the region between the nozzle and the lifted flame edge, leading to stronger partial premixing in the fuel core. Consequently, the overall flame becomes less luminous.

As the air speed increases (to ~3.0 m/s), the overall flame shape does not change much and the main flame body tends to be nearly parallel to the cross flow direction. The flame leading edge, which has a nearly vertical shape, moves toward the downstream of the air flow. The flame becomes bluer and much less luminous, while it also becomes to be elongated to some extent in the horizontal direction.

As the air speed increases further to an excessive level (over ~3.0 m/s), a stable flame cannot be sustained. Similar to the