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Brief Communications

Lift-off of jet diffusion flame in sub-atmospheric pressures: An experimental investigation and interpretation based on laminar flame speed

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ABSTRACT

This paper reveals lift-off behavior of jet diffusion flames in sub-atmospheric pressures less than 100 kPa, in view of that the current knowledge on this topic is limited for normal pressure conditions. Physically, the variation of ambient pressure may have significant influence on the lift-off behavior of jet diffusion flames due to the change of some critical parameters such as laminar flame speed. In this work, experiments are conducted in a large pressure-controllable chamber of 3 m (width) × 2 m (length) × 2 m (height) at different sub-atmospheric pressures of 60 kPa, 70 kPa, 80 kPa, 90 kPa as well as at normal pressure of 100 kPa. Axisymmetric turbulent jet diffusion flames are produced by nozzles with diameters of 4 mm, 5 mm and 6 mm using propane as fuel. It is revealed that the lift-off height increases as the pressure decreases and being much higher than that in normal pressure condition. The laminar flame speed with its dependency on pressure is introduced to interpret such behavior based on classic Kalghatgi model. It is found theoretically that the lift-off height has a power law dependency on pressure by P^{1-n}, where n is overall reaction order of the fuel which is usually larger than 1 indicating a negative power law function with pressure (for example $p^{-0.75}$ for propane as $n = 1.75$) as well verified by the experimental correlation. Finally, a global model is proposed by including such pressure dependency function into the Kalghatgi model, which is shown to well collapse the experimental results of lift-off heights of different sub-atmospheric pressures.

1. Introduction

Lift-off phenomena, in which the flame base detaches from the burner exit, is of great practical significance in understanding the jet diffusion flame stabilization mechanisms. Studies on lift-off behavior of jet diffusion flames have received focused attentions all along. Different mechanisms have been proposed to interpret the lift-off phenomenon.

A premixed flame turbulence intensity theory is firstly proposed by Vanquickenborne [1] and others [2], in which it is explained that the premixed fuel–air mixture flame base travels against the fuel stream at the speed that equal to the local flow velocity. Then Peter and his coworkers [3,4] have proposed the critical scalar dissipation concept claiming that the flame extinct when the scalar dissipation rate exceeds the critical condition. Broadwell et al. [5] has considered the instability of the turbulent diffusion flame based on two ratios of time, namely: the time associated with the re-entrainment of hot products into the fresh reactants and the characteristic chemical reaction time. Moreover, another principle, called triple flame theory, has been proposed [6–8], as one kind of edge flame that can be encountered in non-premixed mixing layers, consisting of a lean and a rich premixed flame wing together with a trailing diffusion flame all extending from a single point. Chung [6,7] has explained the lift-off flame stabilization mechanism based on this theory.

Among these theories, the premixed flame turbulence intensity theory is simplest and still widely used and showing a wide range of applicability in many experiment [9–13]. Following this theory, Kalghatgi [14] has developed till now one of the most classic relation that the flame lift-off height varies linearly with the jet exit velocity independent of the burner diameter as follows:

$$\frac{\rho_e S_L h}{\mu_e} = C\left(\frac{U_e}{S_L}\right) g(\bar{\rho}) \qquad (1)$$

where h is the flame lift-off height, S_L is the laminar flame speed, C is a constant, ρ_e is fuel density at the nozzle exit and ρ_∞ is ambient air density, $\bar{\rho} = \frac{\rho_e}{\rho_\infty}$ and $g(\bar{\rho}) = 0.04 + 0.46\bar{\rho} + 0.5\bar{\rho}^2$ are the density

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Nomenclature

d	nozzle diameter (m)
E_A	the activation energy (J/kmol)
J	momentum (kg (m/s))
h	lift-off height (m)
$\bar{\dot{m}}_F'''$	mean volumetric mass production rate over reaction zone (kg/s m^3)
n	overall reaction rate
P	pressure (Pa)
R_u	ideal gas constant (8.31 J/(kmol))
r	flame radical distance (m)
S_L	the laminar flame speed (m/s)
Sc	Schmidt number
T	temperature (K)
u	velocity of the flow (m/s)
$Y_{F,st}$	fuel mass concentration at the stable position
$Y_{F,0}$	the initial fuel mass concentration

Greek symbols

α	the thermal diffusivity (m^2/s)
ρ	density (kg/m^3)
μ	dynamic viscosity (Pa s)
υ	mass oxidizer-to fuel ratio (kg/kg)
μ_e	kinematic viscosity (m^2/s)

Subscripts

∞	environmental
e	fuel
u	unburned gas fuel
B	burned gas fuel
Max	maximum number
X	local number

Others symbol

$\overline{()}$	mean number in the reaction area (K)

parameter in the reaction area, μ_e is the dynamitic viscosity (constant in dependent of pressure).

However, it is noted that all the previous experimental works and correlations for lift-off height are carried out in standard normal atmospheric pressure condition (100 kPa). There is still few work on clarifying the pressure effect on lift-off phenomenon at sub-atmospheric pressure conditions which exists at locations of high altitudes. It has been recently revealed that [15–21], based on a series of experiments carried out in Lhasa city, Tibet (altitude: 3600 m; pressure: 64 kPa), the combustion and diffusion flame behaviors are quite different from those in normal pressure condition in Hefei city (100 kPa). In an early work by Most et al. [22] investigating the changes of flame height with pressures for pool-type diffusion flames produced by porous gas burner with low *Fr* (Froude) number of 6×10^{-5} in a 0.3 m diameter and 1 m height pressure vessel, it has been even found that the flame height variation behavior with pressure shows opposite trend in sub-atmospheric and elevated-pressure conditions, where the flame height increases with ambient pressure in range of less than about 80–100 kPa and decreases with ambient pressure in range of larger than 80–100 kPa. Physically, the variation of ambient pressure may have significant influence on the lift-off behavior of jet diffusion flames due to the change of some critical parameters such as laminar flame speed as used in Eq. (1). In a previous observation [21] based on experiments carried out correspondingly in Lhasa city (64 kPa) and Hefei city (100 kPa), the lift-off height is revealed to be much higher in the 64 kPa sub-atmospheric pressure than that in normal standard pressure (100 kPa). However, as only one sub-atmospheric pressure are considered in this work, what is the dependency of lift-off height on sub-atmospheric pressures is still a question to be answered, which needs more sub-atmospheric experimental data, however still none in the literatures.

So, in this work, experiments are carried out in a designed laboratory chamber to reveal the lift-off behavior of turbulent jet diffusion flames at sub-atmospheric pressures ranging from 60 kPa to 90 kPa, as well as in normal pressure of 100 kPa. The lift-off height data is then correlated and interpreted according to Kalghatgi model (Eq. (1)) based on the dependency of laminar flame speed on pressure.

2. Experimental

Figure 1 depicts a schematic of the experimental facility and measurement setup consisting of a flow supply system, a 2 m long

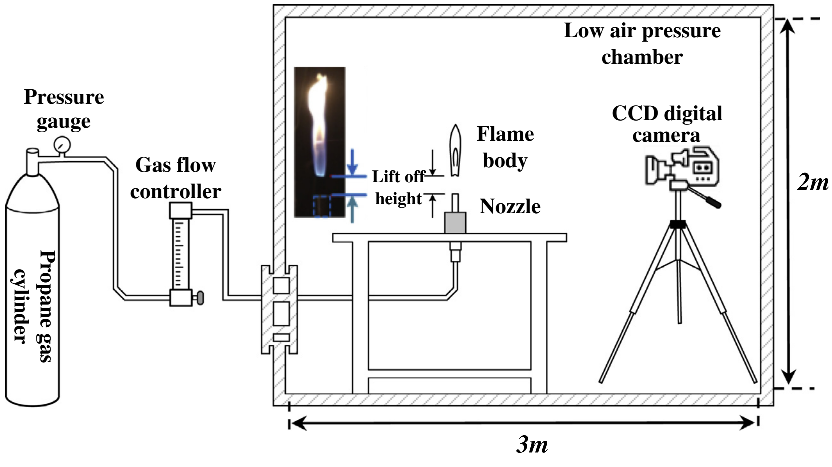

Fig. 1. Experimental facility.