Lift-off Behavior of Horizontal Subsonic Jet Flames Impinging on a Cylindrical Surface

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ABSTRACT

This paper presents a systematic experimental study on the lift-off behavior of jet flames impinging on a cylindrical surface by conducting horizontal jet fire experiments. In the tests, the fuel exit velocity was varied between 8.5 and 73.1 m/s, while the internal diameter of the nozzle was 2.0, 3.0, and 4.2 mm. The nozzle-to-surface spacing was set to be infinite (corresponding to free jet flame), 15, 20, and 25 cm. The flame lift-off distance was observed to be between 0.46 and 20.97 cm. This distance was accurately calculated by using an image visualization technique to reconstruct the image frames of a camera. It was found that the lift-off distance depends on not only the exit velocity but also on the nozzle diameter of the free jet flame. The proportionality of lift-off distance to exit velocity increases as the nozzle diameter increases. It is also indicated that the exit velocity, nozzle diameter and nozzle-to-surface spacing have a complex coupled effect on the jet flame lift-off behavior. For the 2.0 mm diameter nozzle, the lift-off distance of a jet flame impinging on a cylinder increases more remarkably than that of free jet flame. The lift-off distance first increases and then remains the same as the exit velocity increases for all nozzle-to-surface spacings. For the 3.0 mm diameter nozzle, the lift-off distance is only affected at a nozzle-to-surface spacing of 15 cm. For the 4.2 mm diameter nozzle, the cylinder has no effect on the lift-off distance regardless of the nozzle-to-surface spacing. The dimensionless flow number expression for the lift-off distance of free and impinging jet flames in the subsonic regime provides the best fit, after consideration of four different available correlations that are evaluated against the experimental measurement in this paper.

KEYWORDS: Lift-off distance, jet flame, impinging jet, subsonic.

INTRODUCTION

Jet fires caused by accidental fuel gas leakage can increase the scale of an accident by impinging on such structural elements as pipes and tanks. This process, known as the domino effect, has been reported to be responsible for some disastrous events, e.g. the San Juanico disaster of 1984 [1]. In such events, the most common scenario involved jet flames impinging on a cylindrical surface. Even though impinging flames have been applied in different fields of metal heating and melting, chemical vapor deposition, and even aerospace, most researchers only focused on the heat transfer aspect of the process [2], and neglected the flame geometric shapes and flame instabilities. However, the flame instabilities consisting of lift-off and blow-off are important phenomena in combustion and in the fire safety field [3, 4].

In general, a free jet diffusion flame lifts off away from the burner nozzle and forms a stable lifted flame, as the exit velocity increases beyond the lift-off stability limit [3]. Although there are several

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competing theories for explaining the behavior of lifted diffusion flames, none of them is entirely satisfactory. These theories may roughly be classified into four main categories. They include theories based on (i) the premixed flame propagation model [3, 5, 6], (ii) the extinction of laminar diffusion flamelets [7, 8], (iii) the large-scale turbulent structures [9, 10], and (iv) the concept of triple flames [11]. Even though all the theories seem to include the correct mechanisms, their application is strictly limited to vertical jet flames. In particular, some empirical correlations are developed for the lift-off distance by fitting experimental data of vertical jet flames.

However, the available lift-off distance correlations need further evaluation as they are used for horizontal jet flames. Peters and Göttgens [12] proposed an approximate solution to calculate the flame trajectory of large buoyant jet diffusion flames with the jet direction from vertical to horizontal. Similar work has also been done by Kim et al. [13] for hydrogen jet flames with the jet Reynolds number of 2400. Johnson et al. [14] investigated the flame shape and external thermal radiation of large-scale horizontal natural gas jet fire. Siebers et al. [15] focused on the effects of in-cylinder gas oxygen concentration on the flame lift-off of a horizontal direct-injection diesel fuel jet fire. Smith et al. [16] experimentally explored the effects of buoyancy and momentum on the global characteristics of horizontal propane jet flames, such as flame dimensions, centerline trajectory, emission indices, radiative fraction. Gopalaswami et al. [17] and Zhang et al. [18] investigated the flame length, lift-off distance, and flame area of horizontal propane jet flames. The exit velocities varied from 25 m/s to 210 m/s, and the flame lengths from 1 to 6 m. Zhou et al. [19] reviewed correlations of jet flame lift-off distance, flame length, and radiative fraction, and proposed a line source model to predict the heat flux of horizontal jet flame. Additionally, there are some limited research studies on the flame structure of impinging jet flames. For example, Johnson et al. [20] simulated an open air sonic propane flame and a subsonic natural gas flame impinging on a 2 m diameter cylindrical target by using computational fluid dynamics. Patej et al. [21] investigated the thermal load and the thermal response of the pipes directly impinged by different hydrocarbon jet flames. But neither study addressed the question of a new lift-off distance correlation nor evaluated the available correlation for horizontal jet flames.

In view of the limitation of the available lift-off distance correlation for horizontal jet flame, this paper attempts to study the flame lift-off distance of horizontal jet flames impinging on a cylindrical surface. First, propane jet fire experiments are conducted with different exit diameters and velocities, and nozzle-to-surface spacings. Comparisons are then made of lift-off distances, to explore the difference between vertical, horizontal, free, and impinging jet flames. Finally, four different available lift-off distance correlations are evaluated against the experimental measurements of free and impinging horizontal jet flames, with the aim of developing a lift-off distance correlation for horizontal jet flames.

EXPERIMENTAL

Figure 1 depicts the experimental facility and measurement setup. It consists of a fuel supply system and a jet nozzle of stainless steel. The nozzle diameter was varied from 2.0 mm, 3.0 mm to 4.2 mm, with a length of 15 cm. Commercially pure propane was used as fuel and its supply rate was recorded by an Alicat® mass flow controller with an accuracy of ±0.2% of reading + 0.8% of full scale. With the mass flow controller, the fuel exit velocity was set to be 8.51 m/s to 73.10 m/s, with subsonic flow in all tests. A hollow steel cylinder with outer and inner diameters of 8.9 cm and 8.6 cm, was used as target. The horizontal jet flame was set to be normal to cylindrical surface in the test. The spacing between the burner nozzle and the cylindrical surface was 15, 20 and 25 cm, and a free horizontal jet flame was also studied. The spacing was selected to ensure that the size of free jet flame would be at least comparable to that of the impinging jet flame for most of the experimental conditions, and the specific geometrical features could be easily extracted, using an image processing technique. A Digital Video of sensor size 1/2.5 inch with 3840×2160 pixels was used to record the flame at 25 frame per second. The flame video was decompressed into flame images (40 s, nearly 1000 frames), and these images were further processed by the Otsu method [22] to obtain the flame presence probability contours as shown in Fig. 2. The maximum flame lift-off was obtained by measuring the distance from the nozzle outlet to the starting tip of the flame contour line of 50% probability, shown in Fig. 2.

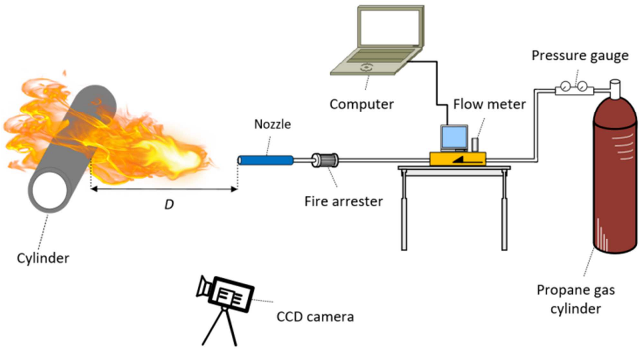


Fig. 1. Schematic diagram of experimental setup.

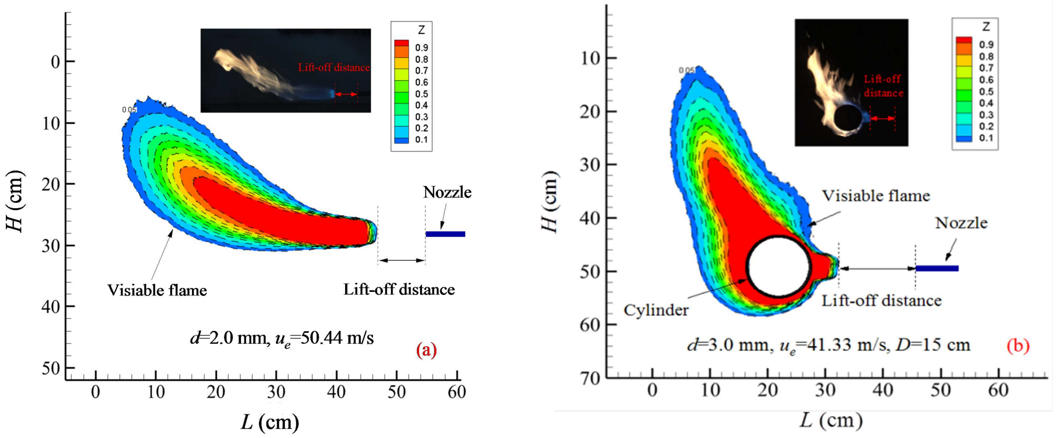


Fig. 2. Flame lift-off quantification according to flame appearance intermittency contour. (a) Free jet flame; (b) Impinging jet flame.

RESULTS AND DISCUSSION

Lift-off of horizontal free jet flames

Several researchers [23, 24] have proposed that the lift-off distance can be related to the global strain rate defined as the ratio of the exit velocity to the nozzle diameter. Figure 3 shows a comparison of the dimensionless lift-off distance with the global strain for horizontal jet flames. Given the limited research on horizontal jet flames, the lift-off behavior has lacked attention. The data provided by Gopalaswami et al. [17] and Zhang et al. [18] are amongst the few available. Data analysis reveals that the lift-off distance of the horizontal propane jet flame is also proportional to the exit velocity, but that the nozzle diameter also has a significant effect on the lift-off behavior. As shown, the proportionality of lift-off distance to exit velocity increases as the nozzle diameter increases. By contrast, using the lift-off data from Kalghatgi et al. [3], Santos et al. [24], and

Palacios et al. [25], with nozzle diameters of 4.06 mm to 43.1 mm, Zhou et al. [19] found that the nozzle diameter has no effect on the lift-off distance versus the exit velocity for vertical propane jet flames. A universal correlation was proposed, with a proportionality of factor of 2.13×10^{-3}.

Vanquickenborne and Van Tiggelen [5], in their early work employed a premixed flame propagation model to explain the stabilization mechanism of lifted diffusion flames. They considered that the premixed nature of the fuel-air mixture controls the flame base location where a stoichiometric composition is achieved. In such a region, the turbulent burning velocity equals the mean flow velocity. Later, assuming a turbulent flame propagating through a premixed fuel-air mixture, Kalghatgi [3] further proposed a scaling law to fit the lift-off distance of vertical jet flames with a wide range of exit velocity (u_e), nozzle diameter (d) and fuel type. With such scaling law, the lift-off distance (l_f) can be described by:

$$Re_{lf} \equiv l_f S_L / \nu_e \sim (u_e/S_L)(\rho_e/\rho_\infty)^{1.5}, \tag{1}$$

where Re_{lf} is the local turbulence Reynolds number based on the integral length scale, ν_e is the fuel gas kinematic viscosity, S_L is the maximum laminar burning velocity of the fuel-air mixture, and ρ_e, ρ_∞ are the densities of fuel gas and ambient air, respectively.

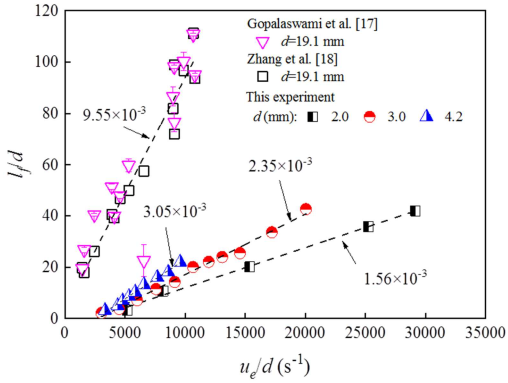


Fig. 3. Dimensionless lift-off distance versus global strain rate for horizontal propane jet flames of different nozzle diameters.

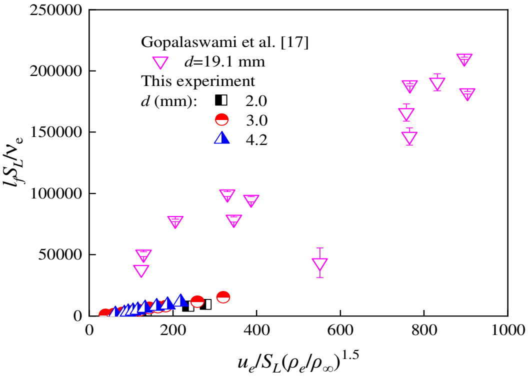


Fig. 4. Lift-off distance fitted by the correlation of Kalghatgi et al. [3] for horizontal jet flames.

As shown in Fig. 4, Eq. (1) correlates the lift-off distance of horizontal jet flames with different nozzle diameters. The scatter becomes apparent as the nozzle diameter reaches 19.1 mm. Kumar et al. [26] also found the deviation when using Eq. (1) to correlate the lift-off of vertical jet flames, especially for large $(u_e/S_L)(\rho_e/\rho_\infty)^{1.5}$. Kalghatgi's dimensionless analysis is unable to explain the effect of nozzle diameter on lift-off distance. Since the same image processing technique for flame base location was applied by this work and Gopalaswami et al. [17], the reason for the major discrepancy between different nozzle diameters was considered to be the inherent inadequacy of Eq. (1). Note that Eq. (1) is based on the premixedness model, which assumes that the lifted flame stabilization is controlled by relatively small turbulent structures. Also note that this model does not incorporate the intermittency of turbulent flow [6].

Broadwell et al. [9] proposed another correlation that successfully attempts to correlate the lift-off distance of a vertical jet flame. This model is based on the idea of large-scale motions in the turbulent jet that can maintain the lifted flame stabilization. In detail, the hot reaction products that are expelled to the edges of the jet by large turbulent vortices are re-entrained to ignite the fresh fuel-air mixture in the lift-off region. His correlation for lift-off distance can be written as:

$$l_f \sim \left[u_e d \left(\rho_e / \rho_\infty \right)^{1/2} \kappa / S_L^2 \right]^{1/2}, \tag{2}$$

in which κ is the thermal diffusivity. Equation (2) can be revised in the dimensionless form of $l_f / d\sqrt{\rho_e/\rho_\infty} \sim \sqrt{\left(\kappa/S_L^2\right) / \left(d\sqrt{\rho_e/\rho_\infty}/u_e\right)}$ in which the two terms, κ/S_L^2 and $d\sqrt{\rho_e/\rho_\infty}/u_e$, provide the measure of two characteristic times. The first one is the characteristic chemical reaction time, while the other is the mixing time of re-entrained hot products with fresh reactants.

As shown in Fig. 5, Eq. (2) correlates well the lift-off distance of horizontal jet flames with different nozzle diameters. The equations shows how the nozzle diameter affects the lift-off distance in detail. However, it is stressed that the mixing time of re-entrained hot products into fresh reactants is hard to determine. It is controversial to use the expression $d\sqrt{\rho_e/\rho_\infty}/u_e$, in Eq. (2), to accurately calculate the mixing time. Pitts [6] suggested a stricter approach, treating the mixing time as that for re-entrainment of hot products at the upstream edges of large-scale vortices. Note that the large-scale inviscid motions, rather than the small-scale turbulent structures, are the source of lift-off stabilization. Figure 6 presents the comparison in the lift-off distance fitted by Eq. (2) between the horizontal and vertical propane jet flames. As shown, Eq. (2) can fit both well, but the horizontal jet flame shows a trend that is different from that of the vertical flame data. The lift-off distance of vertical jet flames shows a linear relationship, while such a relationship is complex for horizontal jet flames.

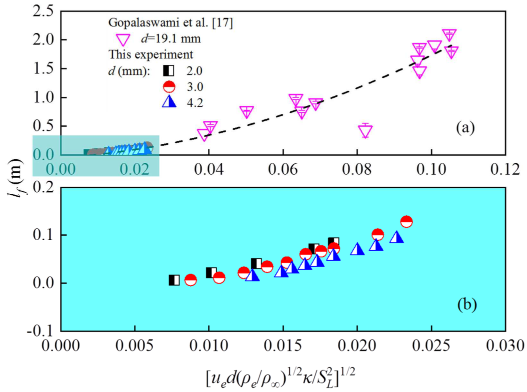


Fig. 5. Lift-off distance fitted by the correlation of Broadwell et al. [9] for horizontal jet flames. Bottom is an enlarged view of the rectangular shaded area.

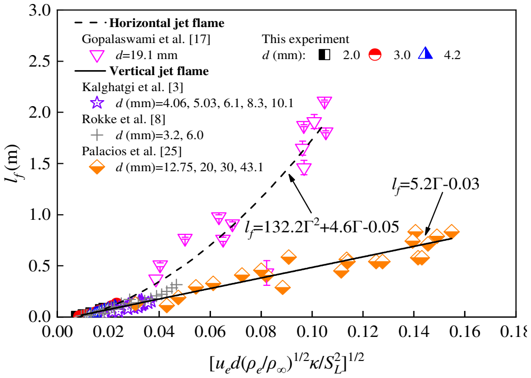


Fig. 6. Lift-off distance fitted by the correlation of Broadwell et al. [9] used for both vertical and horizontal propane jet flames.

Miake-Lye and Hammer [10] also obtained a linear relationship of lift-off distance for vertical jet flames. It is based on the idea that large-scale coherent motions dominates the turbulent jet. By reasoning similar to that by Broadwell et al. [9], the stability criterion is expressed in terms of the critical strain rate that equals the inverse of the chemical reaction time:

$$l_f \sim \left(\kappa/S_L^2\right)\left(Z_{st}/Y_f\right)u_e, \tag{3}$$

where Z_{st} is the mass fraction of pure fuel in air at stoichiometric conditions, and Y_f is the mass fraction of fuel in the jet fluid. Figure 7 presents the lift-off distance correlated by Eq. (3) for both vertical and horizontal jet flames. As shown, the inferred linear relationship is difficult to reproduce. In particular, a significant deviation is observed in the case of large nozzle diameters. The effect of flame speed and thermal diffusivity should be excluded, given the somewhat different values of S_L and κ used in [3, 27, 28]. Thus, such deviation can be mainly attributed to the overly simple chemistry used in the strain-out condition. In addition, Upatnieks et al. [29] used cine-particle imaging velocimetry to measure the lift-off distance of vertical jet flames and assessed the poor validity of Eq. (3), for the correlation between flame propagation and passage of large eddies, not considered by Miake-Lye and Hammer [10]. However, the interaction between the large-scale structure and the flame zone is shown by Schefer et al. [30], who performed planar imaging measurements of CH_4, CH, and temperature of a jet flame. Later, a study by Lyons [31] concluded that the impact of large-scale structures is significant as the turbulent/reaction zone interaction increases and strengthens.

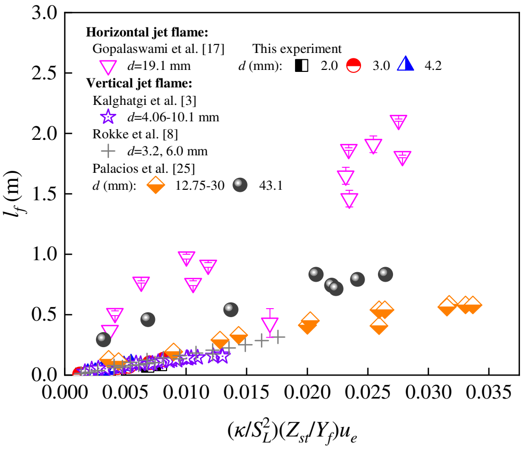
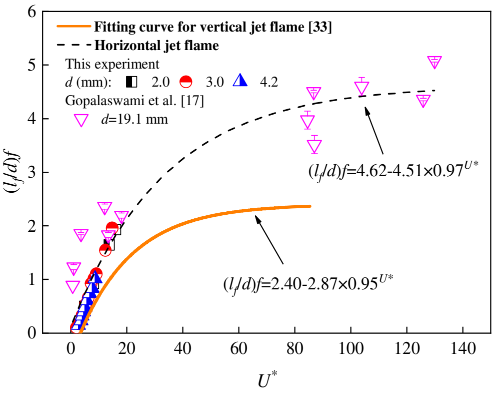


Fig. 7. Lift-off distance fitted by the correlation of Miake-Lye and Hammer [10] used for both vertical and horizontal propane jet flames.



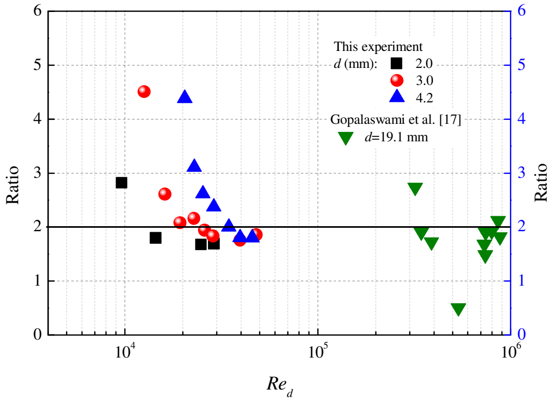


Fig. 8. Lift-off distance fitted by the correlation of Bradley et al. [32] used for both vertical and horizontal jet flames.

Fig. 9. Lift-off distance ratio of horizontal to vertical jet flames versus Reynold number.

Recently, Bradley et al. [32] made some progress in more practical, generalized correlations for the extensive experimental data of flame dimensions of vertical jet flames in both subsonic and sonic regimes. Their main innovation involves a dimensionless flow number that related to the Karlovitz stretch factor in premixed turbulent combustion. The dimensionless flow number (U^*) is:

$$U^{*}=\left(u_e/S_L\right)\left(\delta/d\right)^{0.4}\left(P_i/P_{\infty}\right), \tag{4}$$

in which δ is the laminar flame thickness, given by $\delta=\nu_e/S_L$ at the ambient air conditions, and P_i, P_a are the initial stagnation and atmospheric pressures, respectively. The dimensionless flow number was used to fully correlate the lift-off distance for vertical jet flames of different fuel gases, by introducing the ratio of fuel to air moles (f) in fuel–air mixture for maximum burning velocity [32]. Figure 8 presents the dimensionless lift-off distance versus dimensionless flow number for horizontal propane jet flame, as well as the fitting curve of vertical jet flame in [33]. As shown, the horizontal jet flame holds a larger lift-off distance as the dimensionless flow number is the same.

Figure 9 shows the ratio of lift-off distance between horizontal to vertical jet flames versus the exit Reynolds number ($Re_d = u_e d/\nu_e$). As shown, the ratio approaches nearly two as the exit Reynolds number increases. Nevertheless, such a ratio can help to assess the hazardous scope and consequence of large horizontal jet fires with the available behaviors of vertical jet fires.

LIFT-OFF OF HORIZONTAL JET FLAMES IMPINGING ON A CYLINDER

In order to quantify the effect of the cylindrical surface, near the nozzle, on lift-off distance, as mentioned in the section describing the experiments, the spacing between the nozzle exit and the cylindrical surface, *D*, varies from 15 to 25 cm. Figure 10 demonstrates the effect of the spacing on the normalized lift-off distance versus the global strain rate, for three different nozzle diameters, as well as typical flame photos, with increasing exit velocity for *D* = 15 cm and *d* = 3.0 mm.

As indicated in Fig. 10 (a), the lift-off distance of a jet flame impinging on a cylindrical surface increases more remarkably than that of a free jet flame for the nozzle of 2.0 mm in diameter. It is of interest to observe that the lift-off distance of impinging flame first increases, and then remains stable as the exit velocity increases. In particular, the lift-off distance will reach the nozzle-to-surface spacing as the exit velocity approaches the blow-out limit (see the data in the dashed circles of Figs. 10 (a) and 10 (b) and the last flame image in Fig. 10 (d)). A plausible reason for this phenomenon might result from the complex interaction between the high-temperature jet flame and the cylindrical surface characteristic. It is known that propane fuel flow undergoes a conversion from a gas-liquid mixture to pure gas with the increase in release pressure or exit velocity. Gómez-Mares et al. [34] concluded that flames fed by a two-phase flow mixture are luminous and yellow, while those fed by gas are nearly transparent and blue. As shown in Fig. 10 (d), the impinging flame was also observed to turn from yellow to blue, as the exit velocity increased.

There seem to be two different mechanisms for interpreting the lift-off behaviors of impinging jet flame in such a geometric configuration. In the range of low exit velocity, the soot indicated by bright yellow color plays an important role in heat radiated by jet flames [17], and as seen in Fig. 11 (a), the soot deposits on the contact surface after the jet flame impingement, due to the thermophoresis [35]. These opaque particles escape from the hot flame zone and move towards the cold pipe wall surface where a sharp temperature gradient exists [21]. In this case, the downstream lift-off behavior was not affected, and the lift-off distance still fits the linear law. On the other hand, in the range of high exit velocities, the transparent jet flame causes an oxidation of the steel pipe, resulting from high temperature, as indicted in Fig. 11 (b). So the upstream high temperature oxidation of the alloy, accompanied by intense thermochemical heat release [2], dominates the maximum limitation of downstream lift-off distance of the impinging jet flame. In Fig. 10 (b), the lift-off distance of the impinging jet flame is still affected by the cylindrical surface, as the spacing is 15 cm. However, when the spacing increases further, the cylindrical surface has no effect on lift-off distance, and the same situation was also observed in all test conditions for *d* = 4.2 mm.

Obviously, the spacing should be also a main factor that affects the lift-off distance of the impinging jet flame. Overall, the exit velocity, nozzle diameter and nozzle-to-surface spacing hold a complex, coupled effect on the lift-off behavior of impinging jet flames. It seems that the effect of cylinder on impinging jet flame would appear at the high exit velocity as the nozzle diameter and nozzle-to-surface spacing decrease.

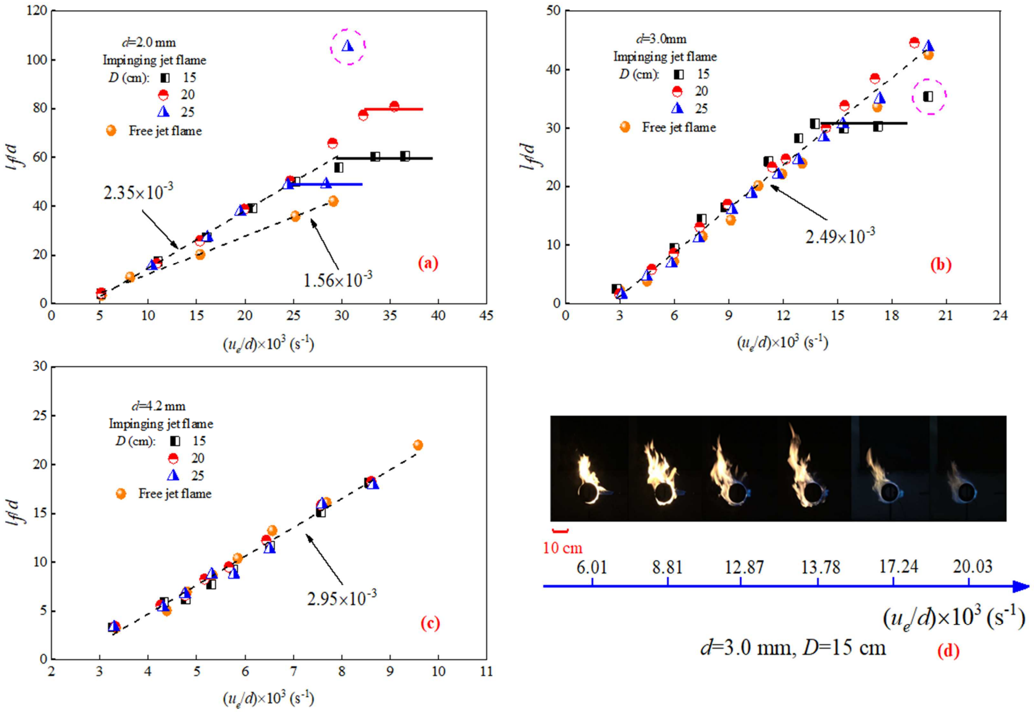


Fig. 10. Dimensionless lift-off distance versus global strain rate for horizontal propane jet flames impinging on a cylindrical surface for d = 2.0 mm (a), 3.0 mm (b), and 4.2 mm (c), and typical flame images versus exit velocity for D = 15 cm and d = 3.0 mm.

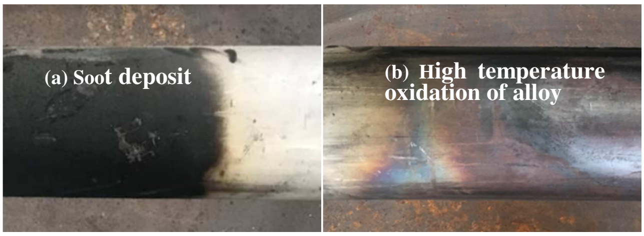


Fig. 11. Evolution of the pipe wall surface due to jet flame impingement. (a) soot deposit; (b) high temperature oxidation of alloy.

Figure 12 presents the lift-off distance fits for impinging jet flames with different available correlations. These attempted correlations for lift-off distance proposal are those from Kalghatgi et al. [3], Broadwell et al. [9], Miake-Lye's and Hammer [10] and Bradley et al. [32], which are shown in Figs. 12 (a), (b), (c) and (d), respectively. As can be seen, the correlations of Kalghatgi, Miake-Lye and Bradley are found to fit well the lift-off distance of impinging jet flames. In contrast, there is large scatter resulting from different nozzle diameters for Broadwell's method. This method seems to be not optimal for the lift-off distance correlation of impinging jet flames. Note the disadvantage of Kalghatgi's and Miake-Lye's methods for free jet flames as stressed in the previous discussion. In short, only the methodology of [32] can give a better fit for the lift-off distance of both free and impinging jet flames. As shown in Fig. 13, the method of Bradley et al. can fully characterize the lift-off behavior of free and impinging jet flames. More experimental data on jet flame lift-off are needed to validate Bradley's method, involving a wide range of exit velocity, nozzle diameter, nozzle-to-surface spacing, and target shape and size.

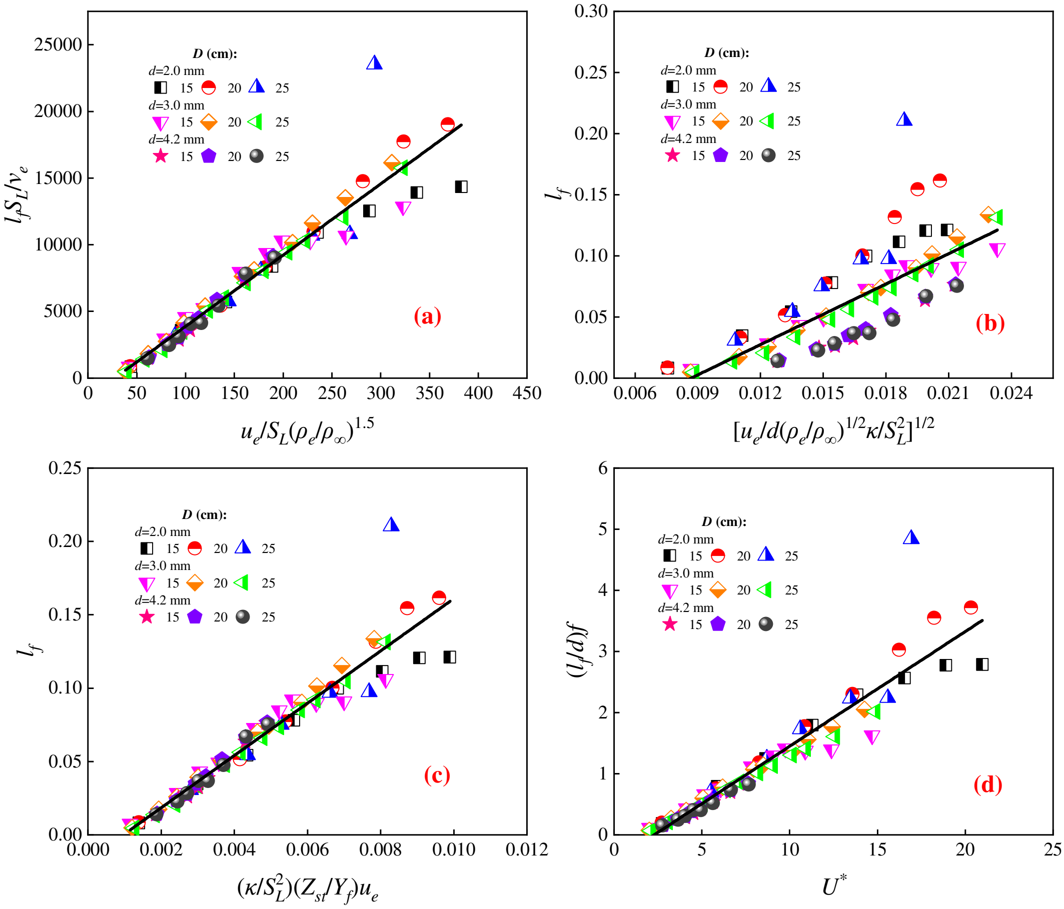


Fig. 12. Comparisons between lift-off distance fittings using different available correlations: (a) Kalghatgi's method [3], (b) Broadwell's method [9], (c) Miake-Lye's method [10] and (d) Bradley et al. [32].

CONCLUSIONS

This paper has reported a systematic experimental investigation on the lift-off behavior of free and impinging horizontal jet flames in the subsonic regime. Comparison in the lift-off distance is conducted between vertical and horizontal jet flames. Four different available correlations of lift-off distance are evaluated against the experimental measurement of free and impinging horizontal jet flames in the subsonic regime. The major findings are as follows:

(1) The lift-off distance is linearly proportional to the exit velocity for vertical jet flames for all nozzle diameters, while the slope of the linear variation of lift-off distance with exit velocity significantly increases as the nozzle diameter increases.

(2) For small nozzle diameter and nozzle-to-surface spacing, the lift-off distance increases linearly,

and then remains constant, finally reaching the nozzle-to-surface spacing as the exit velocity increases. As the nozzle diameter and nozzle-to-surface spacing increase to be large enough, the lift-off distance only becomes a linear function of the exit velocity.

(3) In comparison with correlations of Kalghatgi, Broadwell and Miake-Lye, the dimensionless flow number proposed by Bradley et al. can be used to fit the lift-off distances of free and impinging horizontal jet flames in the subsonic regime.

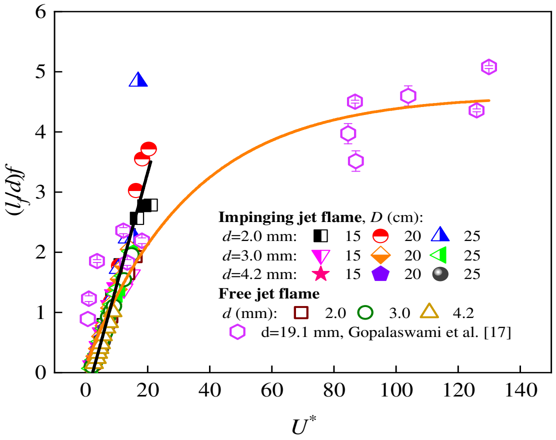


Fig. 13. Lift-off distance fitted by the correlation of Bradley et al. [32] for both free and impinging jet flames.

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