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Hysteresis in stabilization of methane diffusion flames with plasmas

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HIGHLIGHTS

- The liftoff and reattachment velocities are strongly affected by plasmas.
- The hysteresis regime is reduced and eventually disappeared with the addition of plasmas.
- A topological approach is used to predict the change of flame structures in hysteresis region.

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ABSTRACT

The stabilization characteristics of liftoff and reattachment in methane diffusion flames have been investigated experimentally with addition of plasmas. The flame liftoff and reattachment velocities have been measured by varying the applied voltages on plasmas. The results show that the liftoff and reattachment velocities are strongly affected by the plasmas. The difference between these two velocities as well as the flame hysteresis region is reduced and eventually disappeared with the addition of plasmas. A topological approach is put forward to explore the mathematic laws of hysteresis phenomena, and the existent hysteresis and catastrophe laws of flame structure transition are interpreted under the typical operation routes. It is concluded that a change of flame stabilization will occur when the fuel velocity or the applied voltage passes through stabilization boundaries in a special direction.

1. Introduction

Diffusion flames are used in many industry applications due to its safe advantages. The stabilization of diffusion flames always exhibit two states: liftoff and attachment state. An attached diffusion flame lifts off the nozzle when the liftoff velocity is reached and then, if the fuel supply is decreased, the flame propagates upstream until the reattachment velocity is attained, at which point the flame quickly reattaches to the nozzle. A comprehensive series of papers correlating analytical solutions with experimental data have been published to predict the stabilization boundaries for a diffusion flame [1–6].

Since the velocity required to lift an attached flame is higher than that needed for reattachment, a stable diffusion flame can exist as liftoff or attachment state at velocities between these values. The hysteresis in flame stabilization refers to the situation that the flame has dual stabilization positions, and is comprised of a set of velocities which include the liftoff velocity and the reattachment velocity.

This hysteresis of diffusion flames was first investigated by Scholefield and Garside, who concluded that the hysteresis could occur with a sudden decrease in height [7]. Savas demonstrated a big difference of flame structures between attachment and liftoff flames, and reported that such difference accounted for the hysteresis phenomena [8,9]. Shin taken a detailed investigation on flame structures in the hysteresis regime, and concluded the ignition position determined whether flames were attached or lifted [10]. Lin present that the flame base was mostly located at the vortex roll-up position, the roll-up of air into vortex inhibited the flame propagation and eventually caused the hysteresis phenomenon [11]. Lyons parametrically studied hysteresis behaviors by using methane diffusion flames under air-coflow conditions, and present that the co-flows could affect the nature of flame stability as well as the flame hysteresis [12–14].

Combustion enhancement by plasmas or electric fields has been investigated extensively for the purpose of improving flame stabilization. The earliest observation of electric field (plasma) interaction with flames was the work of Brande [15]. They found that flames were attached to electrodes due to the existence of charged particles in the flames. Chung [16–18], Lacoste [19], Bak [20], Belhi [21] and Lyons [22] applied AC or DC electric fields to various

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flames and demonstrated that the plasmas could impose an important effect on the flame structure. Chung summarized the effect of AC and DC electric fields or plasmas on diffusion flames, and demonstrated a reattachment process from a lifted flame to an attached flame with the existence of electric fields [23]. They concluded that the AC voltage amplitude always posed positive effects on flame enhancements, while the AC alternating frequency always posed positive effect on the laminar liftoff velocity as well as negative effect on the reattachment velocity. The DC voltage amplitude had positive effects for the unsteady flames, while had small effects for stationary flames. The combustion enhancement mechanisms by plasmas have mainly been explained as three effects. First is heating effect caused by plasmas [24], second is the enhancement of reaction kinetics by active and excited species produced by plasmas [25], and the third is mainly associated with ionic wind effects [26].

Recently, Vincent-Randonnier demonstrated that when a DBD plasma was activated on a diffusion methane flame, the liftoff height of the lifted flame was significantly decreased [27]. They reported that the reduction in the flame liftoff/reattachment hysteresis could be caused by the DBD discharge, but that the hysteresis couldn't be eliminated at their works. Ju provided a comprehensive review about plasma assisted ignition and combustion, and highlighted that since plasmas has greater kinetic effects on ignition, plasma addition could change the flame ignition/extinction S-curve to a monotonic curve in the hysteresis regime [28].

With the addition of plasmas, the stabilization of diffusion flame is needed to understand the possible change of hysteresis characteristics. This present study experimentally focuses on effects of plasmas on diffusion flame stabilization in hysteresis regimes. With an argon plasma injecting into a methane diffusion flame, the diffusion flame in the hysteresis region is examined. Liftoff and reattachment velocities are collected and analyzed for various plasmas. The methane flame hysteresis features are studied based on topological geometry methods, and the topological rules of diffusion flames in the hysteresis regime are provided and also interpreted with the addition of plasmas.

2. Experimental setup

The schematic diagram of experiments is shown in Fig. 1. A simple floating electrode to generate an atmospheric plasma jet is adopted, which is made of a stainless steel needle with a diameter of 1 mm. When argon is injected into the needle and the alternative voltage (amplitudes up to 20 kV peak-to-peak, repetition rate ranged from 45 kHz to 50 kHz) is applied, a homogeneous plasma jet is generated in front of the end of the needle and into the surrounding air. Such discharge configuration has be shown to concentrate electrical energy into the plasma simply and efficiently [29].

The needle electrode is inserted into a T-shaped quartz tube through a rubble plug, and its tip reaches a same horizontal position with the tube top. The inner and outer diameters of the tube exit are 2 and 4 mm, respectively. The tube top inserted with the needle electrode is acted as fuel jet nozzle, and the mixing between methane and argon occurs at the exit of nozzle. A picture of the fuel jet nozzle is added into Fig. 1 to describe the possible interaction region between diffusion flames and plasmas. When methane is injected from the tube bypass inlet, and a special excitation voltage is applied to the floating electrode, a diffusion methane flame assisted by an argon plasma jet is established in front of the tube exit. With this configuration, the effects of the plasma jet on the flame can be easily observed, and the changes in flame properties (detachment height, flame height, liftoff velocity, etc.) can be quantified.

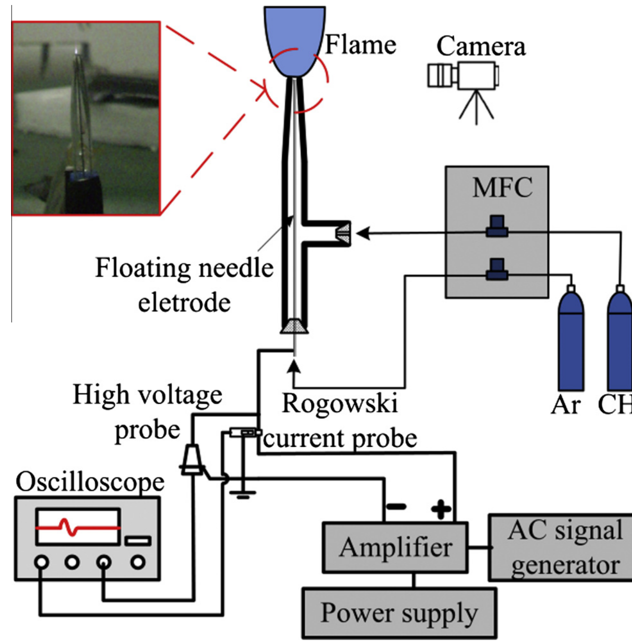

Fig. 1. Schematic diagram of experimental setup.

The setup used for generating and controlling of the discharge is composed of an AC signal generator and an amplifier. The AC generator produces a sinusoidal signal with a low amplitude and with a high frequency. This signal is transmitted to the amplifier for amplitude enhancement. The amplifier output signal is applied to the needle electrode with adjustable voltage amplitudes and repetition frequencies. The current and voltage signals are measured by a Rogowski coil (Pearson 6585) and a high-voltage probe (Tektronix P6015A), and the signals are recorded by a digital oscilloscope (Tektronix DPO4104). Flame images under different experiment conditions are taken by a digital camera (Nikon D7000) with an exposure time up to1/1250 s and a fixed ISO 6400.

3. Structure transition of methane diffusion flames with argon plasma jets

3.1. Effect of plasma jets on the flames' structure

The classical characteristics of a diffusion methane flame are observed. The flame is always attached to the tube until the methane jet velocity V_J is up to 23 m/s, and the flame is mostly of yellow emission. At $V_J = 10$ m/s, the flame base partially detach from the tube. Due to the partially premixing between air and methane at this detached position, the lifted flame is less emissive. H_D increases with V_J until the flame is blown off.

With the addition of plasma jet, the flame structures for different velocities V_J are photographed in Fig. 2. For an attached flame with an excitation voltage amplitude U around 0–2 kV, the flame height remains unchanged and no apparent phenomenon is observed. With the voltage amplitudes increased up to 2 kV, a luminous plasma jet coming is clearly apparent in the flame bottom, and the flame keep attached structure and shook crazily with less emission.

For a lifted flame with an excitation voltage U up to 2 kV, the flame structure is strongly affected by the plasma jet. At $V_J = 20$ m/s and $U = 4$ kV, the lifted flame moves upstream and the flame base becomes slanted, as exhibited in Fig. 2e. Even though the flame is partially-attached, the flame edge is relatively smooth without a cusp-like behavior. With the voltage U increased