Experimental Study on Free Jet Flow with Applied Electric Fields

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1 Abstract

The characteristics of gaseous laminar free-jet flow with having applied electric fields have been investigated experimentally. A single electrode configuration was adopted such that electric fields were applied directly to the nozzle and thus the surroundings could be an infinite ground. Applying DC electric fields does not modify the jet flow so much. At a certain axial distance, the laminar fuel stem was broken down and subsequently it was separated into three parts when AC electric fields with frequencies less than 120 Hz were applied. Over 120 Hz related to a collision response time, the jet flow did not respond to applied electric fields. The breakdown point was identified by varying applied AC voltage and frequency. The jet width increased and then decreased with applied frequency after showing a maximum around 43 Hz. The breakdown height decreased with voltage at a fixed frequency. Such effects of applying electric fields to laminar free jet flow were discussed in detail.

2 Introduction

Lifted flames have been extensively studied to provide a fundamental understanding of flame stabilization and safety in practical burners. A laminar lifted flame, which has the tribrachial structure feature at its base, has to migrate along a stoichiometric contour. Hence the stabilization mechanism has been identified as the balance between the propagation speed of a tribrachial flame along the stoichiometric contour and the local flow velocity [1, 2]. However, lifted flame in practical combustors causes flame instability such as self-excitation and flame extinction [3, 4]. To prevent instability of lifted flame, much research efforts have been devoted to enhance flame stabilization with applied electric fields.

Lawton et al investigated that applying electric field to flame could alter various combustion characteristics through the acceleration of charged particles by the Lorentz force. This acceleration could cause the drift velocity and lead to the increase in kinetic energy such that the mobility and chemical reaction associated with charged particles can be enhanced [5]. Recently, a single electrode configuration has been applied to stabilize turbulent jet flames [6], through interaction of applied electric fields with charged particles in a flame zone. In laminar coflow jet flames, reattachment occurred at higher jet velocities when an AC voltage was applied to the nozzle due to the enhancement of the edge flame propagation speed, thus the stabilization limit of attached flames was extended [7]. In their extended work [8], the enhancement of edge flame propagation speed with AC electric fields has been observed by varying the applied voltage and frequency. The results also showed that similar improvements of the propagation speed were also observed by applying positive and negative DC voltages to the nozzle. However, the detailed interactions of applied electric fields via diffusion, ionic wind and enhanced chemical reaction with non-premixed, premixed and partially flames are still required to be understood further. Besides, interaction of applied electric fields with hydrodynamics may be prerequisite to further understanding of that with flames in various configurations. In the current study, some interesting issues on interaction of applied electric fields with free jet flow are raised, even if detailed analysis on them will be a future work.

2.1 Breakdown of gaseous insulation

In practice, gaseous dielectrics are not free of electrically charged particles, including free electrons. The electrons, which may be produced by applying electric fields, can lead to an initiation for breakdown process. These free electrons produced via the application of electric fields are accelerated from the cathode to the anode by the intensity of electric fields. They acquire a kinetic energy for moving through the electric fields. These free electrons, moving towards the anode, collide with the gas molecules present between the electrodes. During these collisions, part of the kinetic energy of the electrons is lost and is transmitted to the neutral molecules. If these molecules gains sufficient energy, they may be ionized by collision. The number of ionizing collisions by one electron per unit drift across the gap is not constant but subject to statistical fluctuations. Then, the newly liberated electron and the impinging electron are accelerated in the electric fields and an electron avalanche can be generated. Further increase in voltage results in additional ionizing processes. Once these secondary processes take place, ionization increases rapidly with voltage until breakdown occurs. In non-uniform electric fields, considerable ionization may exist in the region of

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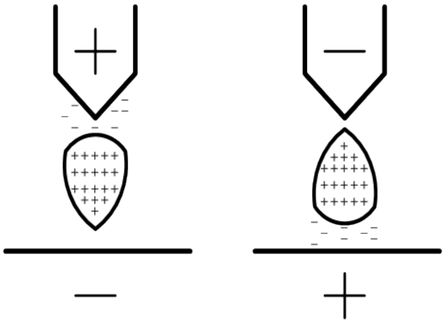


Fig 1. Explanation of the polarity effect of DC flashover of an unsymmetrical arc gap.

high intensity of electric fields even prior to causing a corona discharge. The electrical breakdown of a gas happens due to various processes of ionization. These are gas processes involving the collision of electrons, ions and photons with gas molecules, and electrode processes which take place at or near the electrode surface [9-13].

2.2 Flashover of non-uniform gaps: the polarity effect

If the voltage is increased beyond the corona inception level, some avalanches develop into streamer discharges, bridging the gap to cause a complete flashover. The flashover voltage of a non-uniform gap is therefore much lower than that of a uniform gap of the same size. This polarity effect can be understood by referring to Fig 1, where a positive and a negative sharp electrode are shown. In both cases, the avalanches were formed in the region of the highest field strength (near the sharp electrode). The electrons with a low mass are swept away by the electric fields and are absorbed by the positive electrode. The heavier positive ions move away more slowly and positive space charge builds up near the sharp electrode. In the case of the positive sharp electrode, the positive charge may be seen as an extension of the positive electrode, thus reducing the gap and increasing the field in the remainder of the gap. The ionization processes are therefore accelerated and flashover occurs. Inversely in the case of the negative sharp point, the space charge has a polarity that is different from that of the electrode. The electric fields are thus reduced in the rest of the gap, and higher voltages are required to cause flashover [9-13].

3 Experiment

The experimental apparatus consisted of a nozzle, gas supply systems, an oscilloscope, an amplifier, and a function generator, as shown schematically in Fig 2. The nozzle was made of stainless steel, with inner and outer diameters of 4.5 and 10.6 mm respectively, and a length of 55 cm to ensure fully developed parabolic velocity profiles at the nozzle exit. To prevent external disturbance, the nozzle was surrounded by a plastic mesh of 90 x 90 x 120 cm. The AC power supply (Trek, 10/10B-HS) was operated in the frequency range of 1-2000 Hz by the signal from a function generator. The AC voltage was applied up to 7 kV in the RMS value.

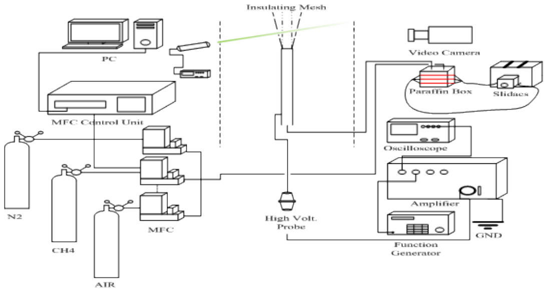


Fig 2. Schematic of experimental set up.

An oscilloscope (Tektronix, TDS1012) was used to monitor the voltage and frequency. High voltage electrode from the AC power supply was connected to the fuel nozzle, while the other electrode was grounded to the building. Thus, the fuel nozzle can be considered as single electrode configuration [6-8]. In this case, the electric fields can be assumed to be formed between the nozzle electrode and infinite ground far away from the nozzle [8]. Behavior of gas flows was recorded with a digital camera.

4 Results and discussion

4.1 Overall flow behavior with AC electric field

Figure 3 shows photographs, which is visualized by using a Mie-scattering technique, with applied electric fields for V_{AC} = 5 kV and f_{AC} = 43 Hz. The flow of N_2 is typically laminar as shown in Fig 3(a), (c), (e), and (g) without electric fields. As the nozzle velocity increases, the laminar gas stem with having AC electric fields was broken down at a certain axial distance and subsequently it was separated into two parts. Such behavior is exhibited in Fig 3(b) and (d) for the gas jet velocities of U_0 = 0.8 m/s and 1.12 m/s corresponding to laminar and breakdown flows, respectively. When the nozzle velocity further was increased, the gas flow was utterly sprayed as shown in Fig 3(h). This phenomenon is similar to electrical breakdown as mentioned above, and it implies that AC electric fields can affect not only flames but also fluid flows in front of the flames. We have also tested the DC electric fields and found that applying DC electric fields did not modify the jet flow so much. In the following, we will focus on the effect of AC electric fields.

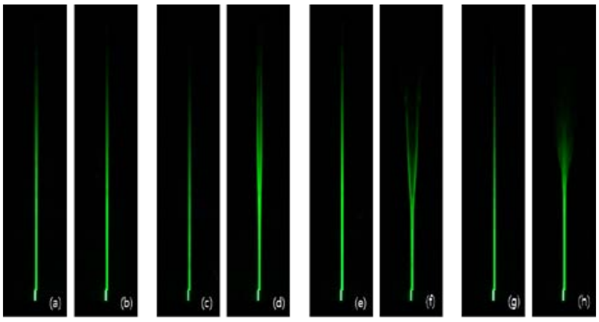


Fig 3. Direct photos of N_2 laminar free-jet flows for: (a) (U_0 [m/s], V_{AC} [kV]) = (0.8, 0); (b) (0.8, 5); (c) (1.12, 0); (d) (1.12, 5); (e) (1.5, 0); (f) (1.5, 5); (g) (3.59, 0); (h) (3.59, 5) at f_{AC}= 43 Hz.

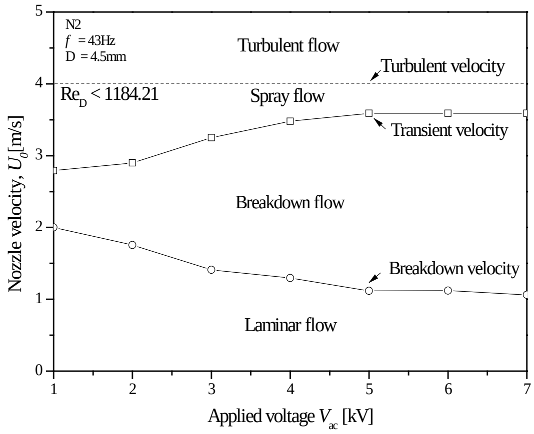


Fig 4. Breakdown, transient, and turblent velocities for f_{AC} = 43 Hz at various applied AC voltages.

As mentioned above, the breakdown of gas occurs for U_0 = 1.12 m/s at V_{AC} = 5kV and f_{AC} = 43 Hz as shown in Fig 3(d). Figure 4 shows the nozzle velocity versus applied AC voltage at f_{AC} = 43 Hz for N_2. The breakdown and transient velocities for V_{AC} = 1 kV is marked at U_0 = 2 m/s and 2.79 m/s, respectively. As the applied voltage increases, the breakdown velocity decreases whereas the transient velocity increases. Prior to breakdown velocities, applying AC electric fields does not modify the jet flow so much. Over turbulent velocities, the flow of gas is turbulent without applied electric fields. In such cases, applying AC electric fields does not also modify the jet flow so much.

Figure 5 shows photographs, which is visualized by using Mie-scattering technique, with applied voltage for U_0 = 1.5 m/s and f_{AC} = 43 Hz. For V_{AC} = 0 kV in Fig 5(A), the flow of N_2 is laminar. As shown in Fig 5(B), the laminar gas stem was broken down at a certain axial distance and subsequently it was separated into three parts when AC electric fields were applied over V_{AC} of 3 kV up to V_{AC} = 7 kV in f_{AC} = 43 Hz (c-g). The breakdown location became closer to the nozzle in increase of applied voltage.

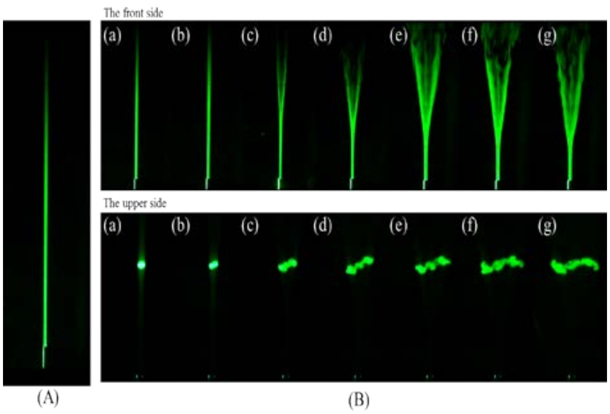


Fig 5. Direct photos of N_2 laminar free-jet flows (A) without electric fields, (B) with applied electric fields for various voltage of (a) V_{AC} = 1, (b) 2, (c) 3, (d) 4, (e) 5, (f) 6, and (g) 7 kV at f_{AC} = 43 Hz and U_0 = 1.5 m/s.

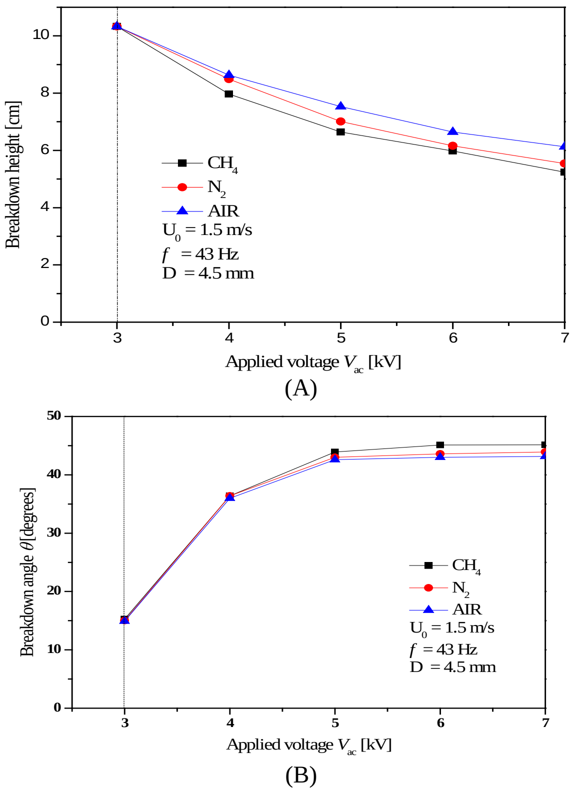


Fig 6. Breakdown height and angle with applied voltage for various gases.

4.2 Effect of AC voltage

As mentioned above, the breakdown location became closer to the nozzle with applied voltage. Figure 6 shows (A) the breakdown height and (B) spread angle versus applied AC voltage at f_{AC} = 43 Hz for CH_4, N_2, and Air. The breakdown height for each gas decreases in increase of applied voltage as shown in Fig 6(A), and is responded differently to further increased AC voltage. The spread angle at the breakdown location for each gas is similar until V_{AC} = 4 kV for U_0 = 1.5 m/s, while that is responded differently to further increased AC voltage as shown in Fig 6(B). When the AC voltage is increased to more than 3 kV, the flow is separated, and then the increase slows down and becomes nearly constant. This implies that the behaviors of breakdown height and spread angle cannot be solely attributed to electron avalanches and detailed mechanism will be a future study.

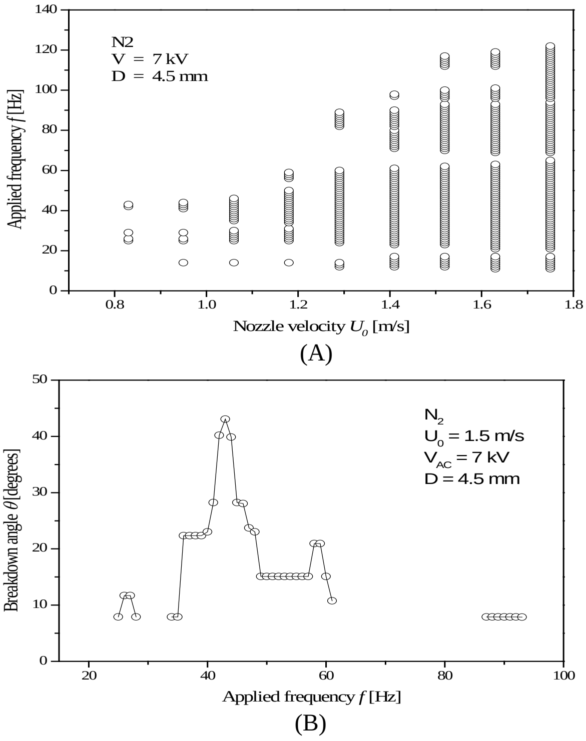
4.3 Effect of AC frequency

Before discussing this phenomenon, it is necessary to examine the collision frequency. Kono et al proposed the collision response time t_c based on the collision frequency z and the ratio of ions to neutral particles R_i, and t_c is presented as $1/(zR_i)$ [14]. Kim et al suggested the collision frequency of a particle with some assumptions [15] as follows:

$$z = \frac{4\pi \sigma^2 P}{\sqrt{\pi m k_B T}}.$$

Here, σ is the collision diameter (4.0×10^{-10} m), P is the pressure, m is the average molecular weight of particles (4.65×10^{-26} kg, nitrogen), k_B is the Boltzmann constant (1.39062×10^{-23} J/K), and T is the temperature. For ambient pressure and temperature, the collision frequency is about $z = 8.3 \times 10^9$ s^{-1} and the corresponding time constant is $t_c = 5.9$ ms. In case of AC, since the voltage is varies, the available time to maintain the same polarity, assuming a constant RMS voltage, is $t = 1/(2f_{AC})$. Then, $t_c = 5.9$ ms corresponds to an AC frequency of about 84 Hz considering the polarity change of AC [16]. In this situation, the ionic wind effect can only be developed for an AC freqeuncy of smaller than around 84 Hz. Because the period of the applied frequency is so much longer than the time scale of most physical processes in the high electric fields that such discharges can be treated as though they were DC.

Figure 7 shows (A) spread angle and (B) the threshold condition of breakdown with frequency for applied voltage of 7 kV. As shown in Fig 7(A), spread angle increases and then decreases with applied frequency after showing a maximum around 43 Hz. When AC electric fields were applied over a certain voltage in a range of frequency less than about 120 Hz as shown in Fig 7(B), the stem of jet flow is separated into three branches over the breakdown location. However, the breakdown was not observed for 1-25 Hz, 28-34 Hz, and 61-87 Hz as shown in Fig 7(A). Fig 7(B) shows that the range of frequency, casing the breakdown, becomes broad in increased velocity. This implies that the breakdown cannot be solely attributed to ionic wind effect.



(A)

(B)

Fig 7. Breakdown in N_2 with applied frequency and nozzle velocity.

5 Conclusions

Gaseous laminar free-jet flows were investigated experimentally with applied AC electric fields. With AC electric fields, the laminar fuel stem was broken down at a certain axial distance and subsequently it was separated into three parts when AC electric fields with frequencies less than 120 Hz. At f_{AC} = 43 Hz, the spread angle exhibited a maximum. The breakdown height of gas decreased with applied voltage at U_0 = 1.5 m/s, while the spread angle increased with applied voltage. However, the breakdown occurred at frequencies larger than the collision frequency calculated with some assumptions, and did not respond to some frequencies even for less than 120Hz. It implies that the breakdown cannot be solely attributed to ionic wind effect. Further analysis will be a future work.

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