Elevated pressure increases the effect of electric fields on ionic wind in methane premixed jet flames

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Abstract

Electric fields are useful for enhancing stability limits of flames, increasing the overall burning rate and reducing soot emissions. The electric body force has been known as a key element behind the aforementioned augmentation, and recent studies have provided clear picture for the resulted flow modification. In this study, we investigate the effects of pressure on an ionic wind by applying transverse electric fields to methane premixed jet flames in a pressurized chamber up to 2 atm. We investigated the voltage-current response by varying the pressure, the equivalence ratio of the mixture, and the flow rate. We found that the saturated current for lean and stoichiometric mixtures were not affected by the pressure, while the saturated current of rich premixed flames changed significantly. We developed a model to predict the voltage-current behavior and the ion-production rate, which we validated using experimental results. Based on our flow field measurements, we found that elevated pressure conditions enhanced ionic wind-driven mass transport. These results support the use of electric fields in a high-pressure environment.

\textit{Keywords}: elevated pressure; ionic wind; electric fields; ion-production rate; saturation current
1. Introduction

The behavior of flames in external electric fields has been studied for several decades. For instance, insights on the fundamental effects of electric fields on flame-generated ions has been well documented by Lawton and Weinberg [1]; the vast information of ions in flames has been well summarized by Fialkov [2] and the first comprehensive ion-mechanism has been developed by Prager et al. [3]; and an overview of applications of the electric field including plasma technology can be found in Zigan’s recent review paper [4]. Recently, stimulated by advances in experimental methods and modeling capabilities [5]–[11], a part of the old insights has been validated revealing a mechanism of the ionic wind to form due to both negative and positive ions, and the flame behaviors have been elaborated emphasizing the importance of the ionic wind. As a result, it has been found that the chemical and thermal effects of electric fields on flames are insignificant, and the ionic wind is mainly responsible for the modified flame’s characteristics, such as a flame speed [9], [11], soot formation [12], [13], and CO emission [14].

Nevertheless, the practical implications of ionic winds on combustion systems with high-Reynolds flows and elevated pressure remain uncertain. For turbulent flames, an increased flame area results in an increased current density, which should positively affect the generation of ionic wind because the electric body force should increase as the current density increases [1].

For higher pressures than atmospheric pressure, the most important factor in predicting the electric body force is the relationships of ion production and ion mobility with pressure. Since ion production limits the total number of ions under the saturated regime and the ion mobility determines the speeds of ions, the ion number density and consequent electric body force can be determined from these two parameters and the electric field intensity. Ion number density in fluid with elevated pressures is expected to increase due to the inverse proportionality of ion mobility with pressure [15], [16]; thus, the electric body force is also expected to increase as a consequence. A previous study investigated turbulent jet flames under pressures up to 10 bar [15]; however, that study was limited by the experimental conditions, and a deduction of the ion-production rate was not possible.
The present study was carried out to address two important questions: i) what is the functional relation between the saturation current and pressure, and ii) does the ionic wind still contribute to altering flame characteristics in elevated pressure. We employed the same jet flame with transverse electric fields that we used in a previous experimental study [8] and installed the system inside a pressurized chamber. Since the previous numerical study [6] has simulated the flame in the atmospheric pressure, qualitatively well predicting the experimentally obtained flow field [8], we believe the present experiment may serve as a reference for a future simulation in a high-pressure condition. Note that such a configuration of a jet flame with transverse electric fields has a long history; Calcote has shown deflected premixed flames [17], Payne et al. have investigated heat transfer and soot deposition to the electrode wall [18], Carleton and Weinberg have demonstrated the electric body force driven convection in a microgravity environment [19], and Shrivastava et al. have used a similar configuration to study a spread rate of candle flames [20].

We chose methane as the fuel because its chemistry including ions is relatively light and can be modeled in a simpler manner [6]. We investigated the electrical current responses with applied voltage, i.e., the voltage-current (V-I) behavior, and the flow fields by varying the pressure, equivalence ratio, and the mass flow rate of methane to study the ion-production rate and ionic wind, respectively.

2. Experiments

2.1. Experimental method

The experimental setup consisted of a quartz tube, two round, metallic mesh electrodes, a pressurized chamber, a high-voltage supply system, and measurement systems. The quartz tube (6-mm inner diameter, 1-mm thickness, 140-mm length), which served as a nozzle, was installed vertically at the center of a bottom plate inside the pressurized chamber (Fig. 1). The two mesh electrodes (80-mm diameter) were vertically placed with an inter-electrode gap of 50 mm. The electrodes were positioned
with the quartz nozzle placed in the center between the two electrodes and with the nozzle exit 30 mm above the bottom of the electrodes, so that the flames were well positioned in the center of the inter-electrode gap [8].

The pressurized chamber had a spherical inner geometry with a 300-mm diameter. The chamber was equipped with six windows of 120-mm diameter at each side and eight ports; the ports were used for a pressure transducer (Keller, PAA-33X/80794), air supply, and electrical connections. The pressure inside the chamber, $P_c$, was increased by supplying air through a port, and the pressure was maintained by a micro-needle valve installed in the exhaust line at the center of a top plate. We considered three pressure conditions as $P_c = 1.13, 1.50, \text{ and } 2.00 \text{ atm}$, so that the pressure ratio was fixed at $1.33 (= 1.50/1.13$ and $2.00/1.50)$ for each increment.

Methane and air were supplied through the quartz tube using mass flow controllers (MKS, 1179A) to establish laminar premixed flames. We selected three equivalence ratios ($\phi = 0.9, 1.0, \text{ and } 1.3$) with various mass flow rates of methane. For the supply of balancing air to fill the chamber, we used a micro-needle valve. Excessive fuel at $\phi = 1.3$ consumes 1–4.5% oxygen in the chamber per minute to form a secondary diffusion flame. However, since we obtained the $V$-$I$ within a minute after applying electric field, the effect of reduced oxygen on the date would be insignificant.

A voltage amplifier (Trek, 40/15, up to 40 kV), which amplified a signal from a function generator (NF, WF1973), applied direct current (DC) electric fields to the inter-electrode gap. We applied high voltage to the electrode on the left-hand side in Fig.1, while the electrode on the right-hand side was connected to the ground. We measured the applied voltage ($V_{DC}$) and electric currents with a high-voltage probe (Tektronix, 6015A) and a current preamplifier (Stanford research system, SR560), respectively, using an oscilloscope (Tektronix, MSO 2024).

We employed a particle image velocimetry (PIV) equipped with a continuous-wave laser at 532 nm (Coherent, Verdi G SLM-series) and a high-speed camera (Photron, SA-X2). The laser beam was expanded vertically and focused over the quartz nozzle, passing through the centers of both electrodes and the center of the quartz nozzle. We seeded TiO$_2$ particles (~0.3µm) through both air
streams in the methane-air mixture and the balancing air. The high-speed camera took images (5,000 frames per second) at right angles with the laser beam’s passage. We used the MATLAB-based PIVlab [21] to analyze the two-dimensional flow fields by post-processing two adjacent images at a time interval of 1/5000s.

![Schematic of experimental setup.](image)

**Fig. 1.** Schematic of experimental setup.

2.2. Experimental design

We preliminarily measured the saturated current ($I_{\text{sat}}$) for various equivalence ratios (0.9–1.5) with a fixed mass flow rate of methane, $m_{\text{CH}_4} = 1.82 \text{ mg/s}$, at $P_c = 1.00 \text{ atm}$ (Fig. 2). The measured $I_{\text{sat}}$ showed a maximum at around $\phi = 1.1$, demonstrating decreased saturated current for both the leaner and richer mixtures. We selected three equivalence ratios, $\phi = 0.9$, 1.0, and 1.3, to investigate the effect of pressure on the ion chemistry in a lean, stoichiometric and rich premixed flame, respectively. Note that the mixture with $\phi = 0.9$ was a leaner limit showing a certain range of flow margin for stable nozzle attached flames, and $\phi = 1.3$ exhibited similar $I_{\text{sat}}$ to that of the flame with $\phi = 0.9$. 
We noticed that, to achieve the saturation current in the elevated pressure condition, a higher applied voltage was required even with the same $\phi$ and $\dot{m}_{\text{CH}_4}$. At $P_c = 2.00$ atm with the stoichiometric flame, the current saturation and electrical breakdown occurred as we applied $\sim 24$ kV and $\sim 32$ kV, respectively; thus, we could investigate the comprehensive $V$-$I$ behavior with the given voltage amplifier.

Lastly, we limited PIV measurements to the stoichiometric mixtures only. Because flow modification due to an electric body force is mainly governed by the ion-production rate and external electric field, extending the investigation to include the lean and rich mixtures is not necessary. Figure 3 shows a range of stable flames in terms of $P_c$ and $\dot{m}_{\text{CH}_4}$. Because there was no universal $\dot{m}_{\text{CH}_4}$ for all tested $P_c$ due to the limits of flashback and blowoff, we had to select two $\dot{m}_{\text{CH}_4}$, 3.43 and 4.55 mg/s, to reasonably investigate the pressure effect from $P_c = 1.13$ atm to 1.50 atm and from $P_c = 1.50$ atm to 2.00 atm, respectively. The ratio of $\dot{m}_{\text{CH}_4} = 4.55/3.43$ was designed to have the same ratio as the pressure ratio (=1.5/1.13), such that the nozzle exit velocity, $u_o$, with $\dot{m}_{\text{CH}_4} = 4.55$ mg/s at $P_c = 1.50$ atm was the same as that with $\dot{m}_{\text{CH}_4} = 3.43$ mg/s at $P_c = 1.13$ atm. We provide detailed experimental conditions in section 3.2 after elaborating on the $V$-$I$ characteristics in section 3.1.
3. Results and discussion

3.1. Voltage–current characteristics

By varying $\dot{m}_{\text{CH}_4}$ for a given $\phi$ and $P_c$, we found that $I_{\text{sat}}$ was linearly proportional to $\dot{m}_{\text{CH}_4}$ only, irrespective of $P_c$, for the mixtures with $\phi = 0.9$ and 1.0. Meanwhile, we found very interesting result in the rich premixed flames ($\phi = 1.3$) showing significant dependence of $I_{\text{sat}}$ on $P_c$—smaller $I_{\text{sat}}$ with higher $P_c$ (Fig. 4). Note that we only know that rich premixed flames have an additional layer of C$_3$H$_3^+$ produced by the late formation of C$_2$H$_2$ [2], [22], [23], whereas, for lean and stoichiometric mixtures, CHO$^+$ formation and a fast proton-transfer to water to form H$_3$O$^+$ are known to be a major ion-production mechanism [2].

The saturation currents, except for $\phi = 1.3$, are expressed as $I_{\text{sat}} = a \times \dot{m}_{\text{CH}_4}$, where $I_{\text{sat}}$ in [$\mu$A], $\dot{m}_{\text{CH}_4}$ in [mg/s], and $a$ is a coefficient in [mC/g] with $a = 3.05$ and 4.65 with correlation coefficients ($R$) = 0.999 and 0.998 at $\phi = 0.9$ and 1.0, respectively. Since a production rate of CH radicals, which initiate the chemi-ionization forming CHO$^+$, is proportional to $\dot{m}_{\text{CH}_4}$, the saturation current shows linear dependence on $\dot{m}_{\text{CH}_4}$ [2]. Note that such a linear relation has been a foundation of a flame ionization detector (FID) in a gas chromatograph [2].
Fig. 4. Saturation currents as a function of $m_{\text{CH}_4}$ for various $P_c$ and $\phi$.

We plotted the $V$-$I$ characteristics at the tested $\phi$ and $P_c$ for a few selected $m_{\text{CH}_4}$ to detail the current response (Fig. 5). As we outlined previously, we found unchanged $I_{\text{sat}}$ for a fixed $m_{\text{CH}_4}$ regardless of $P_c$ at $\phi = 0.9$ and 1.0, as shown in Fig. 5a and Fig. 5b, respectively. Meanwhile, $I_{\text{sat}}$ was significantly affected by $P_c$ at $\phi = 1.3$ for a given $m_{\text{CH}_4}$ (Fig. 5c). Each $V$-$I$ trend showed a typical behavior, i.e., a quadratically increased current with an increased $V_{\text{DC}}$ (sub-saturated regime), and the current became saturated over a certain voltage, indicating $I_{\text{sat}}$ (saturated regime). When we compared the $V$-$I$ trends of the same $m_{\text{CH}_4}$, the critical voltage to enter the saturated regime ($V_{\text{cri}}$) increased with increased $P_c$; $V_{\text{cri}} \sim 16$ kV at $P_c = 1.13$ and $\sim 20$ kV at $P_c = 1.50$ atm for $m_{\text{CH}_4} = 3.43$ mg/s with $\phi = 1.0$, for example (Fig. 5b closed symbols).
Fig. 5. Voltage-current characteristics of the premixed methane/air flames with selected $\dot{m}_{CH_4}$ and $P_c$ at a) $\phi = 0.9$, b) 1.0, and c) 1.3.

Such scattered $V$-$I$ trends could be generalized in terms of $V_{DC}$, $P_c$, and $\dot{m}_{CH_4}$, as in Fig. 6 for $\phi = 0.9$ and 1.0. In general, one can calculate the electrical current by multiplying the number of elementary charges by the speed of their carriers. The number of charges separated from a unit area of a flame is proportional to the field intensity ($E$); thus, the total number of separated charges should be $\sim A_f \times E$, where $A_f$ is the total flame area. The speed of charge carrier can be expressed using the mobility of the carrier ($K_c [m^2/sV]$) as $K_c \times E$, thus, $I \sim (A_f \times E)(K_c \times E)$. Note that, therefore, $I \sim E^2$ in the sub-saturated regime. Now, $A_f$, $K_c$, and $E$ need to be rephrased in terms of the controlled variables.

For the same $\dot{m}_{CH_4}$ at fixed $\phi$, the mass conservation and steadily burning flames for two different pressure conditions give $\rho_1 S_{L,1} A_{f,1} = \rho_2 S_{L,2} A_{f,2}$, where $\rho$ is the density, $u_i$ is the unburned velocity, $A_{f,i}$ is the flame area, and $S_{L,i}$ is the laminar burning velocity. Since the laminar burning velocity of a methane-air premixed flame has been known to be inversely proportional to $P_c^{1/2}$ [24],
finally we obtained $A_f \sim 1/P_c^{1/2}$. In addition, the flame area is proportional to $\dot{m}_{\text{CH}_4}, A_f \sim \dot{m}_{\text{CH}_4}$, in order to consume the incoming mass with the given $S_L$. Next, as the mobility represents a diffusion of charge carriers due to electric fields, it is inversely proportional to the density of the gas, say, $K_{c_2}/K_{c_1} = (P_1/P_2)(T_2/T_1)$, where $P_i$ and $T_i$ indicate pressure and temperature at a state $i$, respectively [15, 16]; thus, we obtained $K_c \sim 1/P_c$. Lastly, although the electric field is a local value, a nominal field intensity, expressed as $E = V_{DC}/L$, could be used for the first-order approximation. Then, the electrical current can be arranged as below.

$$I/\dot{m}_{\text{CH}_4}[\text{mC/g}] = b(V_{DC}^2/P_c^{3/2}) [\text{kV}^2/\text{atm}^{3/2}], \quad (1)$$

![Fig. 6. Generalized V-I relation including the effects of $\dot{m}_{\text{CH}_4}$ and $P_c$.](image)

We found that the linear relationship of $I/\dot{m}_{\text{CH}_4}$ suitably predicted the $V$-$I$ data in the sub-saturated regime for $\phi = 0.9$ and 1.0, as in Eq. (1), with $b = 3.02 \times 10^{-2}$ mC-atm$^{3/2}$/g-kV$^2$ and $R = 0.99$ (Fig. 6). Meanwhile, $I_{\text{sat}}$ were reasonably scaled with $\dot{m}_{\text{CH}_4}$, which is the slope $a$ in Fig. 4 for each $\phi$, irrespective of $P_c$ and $V_{DC}$. Figure 6 also includes the range of measured $I_{\text{sat}}$ (as in Fig. 4), as indicated by the shaded zones and the two representative symbols, i.e., the diamond for the average $I_{\text{sat}}$ and the star for the constant $a$. It is interesting to compare the present $a = 4.65$ mC/g at the stoichiometric mixture with a previously reported one, $I/\dot{m}_{\text{CH}_4}= 4.22$ mC/g [7], for the nonpremixed counterflow.
configuration with axisymmetric electric fields. Although those specific charge-generations are reasonably similar, the experimentally determined constants $a$ and $b$ in Fig. 4 and Eq. (1), respectively, should be limited to the present flames until further investigation and validation. Nevertheless, once $I_{\text{sat}}$ for any $\phi < 1$ is measured for the same system at atmospheric pressure, the overall $V$-$I$ behavior can be predicted for any given $P_c$ and $\phi$.

3.2. Development of ionic wind

One dimensional derivation with a constant current density ($i_c$), which is defined by the electric current in a unit area perpendicular to the field lines, reveals the electric body force, $qE = i_c/K_c$, since $i_c = qK_cE$ with $q$ as the amount of charge [1]. Thus, both energy conservation and momentum conservation result in $v_i \sim i_c/\rho K_c$ for an inviscid flow, where $v_i$ is bulk flow velocity (ionic wind velocity) due to the electric body force. This can be rewritten, regardless of pressure, as

$$v_i \sim i_c$$

(2)

since $\rho K_c$ is constant as outlined by the section 3.1 and the ideal gas law. This implies that we can generate the same degree of ionic wind as long as we induce the same current density for a certain condition by applying a proper electric field. For the saturated regime, since $i_c = i_{\text{sat}} = \text{constant}$, the ionic wind velocity is expected to be irresponsive to an increase in the applied voltage.

However, in a real situation (three-dimensional space), the current density cannot be constant due to the finite flame area and the non-uniform electric field, which is caused by non-uniform distribution of space charge as well as the electrode’s geometry. The current density even cannot be measured; only the overall current through the electrodes can be measured in experiments. In addition, in a viscous fluid, the ionic wind is inevitably accompanied by entrainment, where the one dimensional modeling fails to predict.
Therefore, we analyzed the flow fields with PIV to investigate the two important implications in the 1-D model outlined previously: i) whether the ionic-wind velocity is independent of pressure when $I_{\text{sat}}$ is unchanged, and ii) whether the ionic-wind velocity is irresponsive to the electric field once the saturated regime is reached. We selected seven conditions to obtain comparison data on the flow field, which was influenced by the pressure, applied field intensity, and the ion-production rate, as summarized in Table 1. The corresponding conditions are also shown in Fig. 5b. The exhaust valve was closed during the PIV measurement to avoid the influence of the exhaust flow. The high-speed imaging time was set at 4.37 seconds for each condition, and the pressure increase during this imaging time was less than 5%.

Supplementary movie 1 shows the evolution of the flow field when $V_{\text{DC}} = 26 \text{ kV}$ was applied to the flame with $\dot{m}_{\text{CH}_4} = 4.55 \text{ mg/s}$ at $P_c = 2.00 \text{ atm}$. We found a periodic fluctuation in the flow motion, which we did not observe in our previous study carried out in an open-air environment [8]. This fluctuation might be attributed to the flow interaction with the chamber wall. We averaged 5,000 instantaneous flow fields during the final second (3.37–4.37s) to represent each case in Table 1.

Table 1. Selected conditions for PIV analysis at $\phi = 1.0$.

<table>
<thead>
<tr>
<th></th>
<th>$P_c$ [atm]</th>
<th>$\dot{m}_{\text{CH}_4}$ [mg/s]</th>
<th>$u_0$ [m/s]</th>
<th>$V_{\text{DC}}$ [kV]</th>
<th>$E_n$ [kV/cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.13</td>
<td>3.43</td>
<td>1.00</td>
<td>20.0</td>
<td>4.00</td>
</tr>
<tr>
<td>B</td>
<td>1.50</td>
<td>3.43</td>
<td>0.75</td>
<td>20.0</td>
<td>4.00</td>
</tr>
<tr>
<td>C</td>
<td>1.50</td>
<td>4.55</td>
<td>1.00</td>
<td>10.0</td>
<td>2.00</td>
</tr>
<tr>
<td>D</td>
<td>1.50</td>
<td>4.55</td>
<td>1.00</td>
<td>15.4</td>
<td>3.08</td>
</tr>
<tr>
<td>E</td>
<td>1.50</td>
<td>4.55</td>
<td>1.00</td>
<td>20.0</td>
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<tr>
<td>F</td>
<td>1.50</td>
<td>4.55</td>
<td>1.00</td>
<td>26.0</td>
<td>5.20</td>
</tr>
<tr>
<td>G</td>
<td>2.00</td>
<td>4.55</td>
<td>0.75</td>
<td>26.0</td>
<td>5.20</td>
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$E_n$ is nominal field intensity calculated by $V_{\text{DC}}/L$

As shown in the upper row of Fig. 7 (the color code with velocity magnitude), the initial vertically-developed-flow, due to buoyancy as well as jet momentum, was transformed into the horizontally-oriented-flow pattern by the increased ionic wind toward both electrodes as $V_{\text{DC}}$ increased.
for a given flame and pressure. To see the exclusive effect of the applied electric body force on the flow modification, we replotted the result in the lower row with a redefined color code representing only a magnitude of transverse velocity component, $u_x$. The stronger $u_x$ in the right hand side of the nozzle is attributed to the existence of positive ions in this domain [8]. The degree of ionic wind became stronger (Fig. 7C to F) with increased $V_{DC}$, and, particularly in the saturated regime, the increase in $V_{DC}$ (Fig. 7E to F) resulted in the decreased region of ionic wind. We found that the one-dimensional relation of the ionic wind ($v_i \sim i_c$) was not applicable to the three-dimensional case. We also determined that it is not appropriate to evaluate the overall mass flow or momentum induced by a given $V_{DC}$ based solely on the obtained flow fields in the vertical cross-section.

![PIV result showing the effect of increased $V_{DC}$ (C→F) with $m_{CH_4} = 4.55$ mg/s at $P_c = 1.50$ atm. Color code represents the magnitude of $u$ and $u_x$, in the upper row and the lower row, respectively.](image)

Fig. 7. PIV results showing the effect of increased $V_{DC}$ (C→F) with $m_{CH_4} = 4.55$ mg/s at $P_c = 1.50$ atm. Color code represents the magnitude of $u$ and $u_x$, in the upper row and the lower row, respectively.

Furthermore, we found a drastic change in the flow streamlines as $V_{DC}$ increased from 15.4 kV (Fig. 7D) to 20.0 kV (Fig. 7E). At $V_{DC} = 20.0$ and 26.0 kV (Fig. 7E and F), the main burnt stream from the flame, which we expected to move upwards through the center of the PIV images as shown in the reference case, was completely separated from the flame and instead moved towards both electrodes, as evidenced by the downward ambient entrainment forming a stagnant flow pattern above the flame. This behavior is comparable with the previously observed double-stagnant flow pattern caused by a separation of the main flows in the counter-flow burner [7], which occurred only in the saturated regimes. We will investigate a more detailed characteristics in the saturated regime in a near future.
When the pressure increased for a given flame (Fig. 8A→B and F→G) at the fixed $V_{DC}$, the transverse velocity decreased, but the area affected by the electric body force increased. When we compare each flow pattern in Fig. 8, we find that the cases A and F show the separation of the burnt flow with the downward entrainment at the center for $P_c = 1.13$ and 1.50 atm, respectively, whereas the cases B and G still have non-separated flow fields. For $\dot{m}_{CH_4} = 3.43$ mg/s at $P_c = 1.13$ atm (A), $V_{DC} = 20$ kV was sufficiently higher than the saturation moment—$V_{cri} \sim 16$ kV; however at $P_c = 1.50$ atm (B), $V_{DC} = 20$ kV is nearer the critical voltage for $I_{sat}$, as shown in Fig. 5b. Similarly, $V_{DC} = 26$ kV (F) was high enough to produce the $I_{sat}$ at $P_c = 1.50$ atm, but $P_c = 2.00$ atm, $V_{DC} = 26$ kV (G) was around $V_{cri}$ (Fig. 5b).

The increased $\dot{m}_{CH_4}$ for fixed $P_c$ and $V_{DC}$ resulted in a similar range of transverse velocity with an enlarged area of the ionic wind (Fig. 8B→E). We attribute this behavior to the increased flame area (actually the flame height) with the higher $\dot{m}_{CH_4}$, which keeps the ion-production rate in the unit flame area the same.

![Fig. 8. PIV results showing the effect of increased $P_c$ (A→B and F→G) and varied $\dot{m}_{CH_4}$ at $P_c = 1.50$ atm (B→E). Color code represents the magnitude of $u_x$.](image)

Finally, we conclude that the increased pressure should support the ionic wind, although the three-dimensional nature could not be considered in the present planar measurements. To assess a mass transportation due to the ionic wind, $\rho u_{ks}$, we need to estimate the gas density for a given pressure. A first-order approximation should be $\rho \sim P_c$, assuming that the change in temperature in the corresponding fluid is negligible. We replotted Fig. 8 by multiplying $u_k$ by the corresponding $P_c$. When
$P_c$ increased, the mass transport increased due to the ionic wind, both in terms of maximum magnitude and an effective domain as shown in Fig. 9 (A→B and F→G).

![Image of Fig. 9](image)

**Fig. 9.** The effect of increased $P_c$ (A→B and F→G) and varied $\dot{m}_{\text{CH}_4}$ at $P_c = 1.50$ atm (B→E) on the mass flux ($\sim P_c u_x$) due to electric body force. The color code represents the magnitude of $P_c u_x$.

We further postulate that we can practically obtain an even stronger ionic wind effect when elevated pressure is involved. In general, applied voltage to a flame is limited by the breakdown voltage which initiates electrical discharges. However, increasing the pressure prevents the gas medium from experiencing breakdown, as given by Paschen’s Law, indicating that there is much more margin for $V_{DC}$ before it reaches breakdown. Therefore, a higher $V_{DC}$ can be applied under a higher $P_c$, which, in reality, will further enhance the degree of ionic wind. Note that the electrical discharge occurred at $V_{DC} = 20$ kV at $P_c = 1.0$ atm for $\phi = 1.0$ and $\dot{m}_{\text{CH}_4} = 3.04$ mg/s, whereas $V_{DC} = 28$ kV made the discharge happen at $P_c = 1.5$ atm.

4. Conclusions

We experimentally investigated and discussed the pressure dependences of a premixed flame’s saturation current and the degree of ionic-wind generation. We considered a simple methane premixed jet flame installed inside a pressurized chamber, where we investigated lean ($\phi = 0.9$) and rich mixtures ($\phi = 1.3$) as well as stoichiometric mixtures ($\phi = 1$).

As a result of voltage-current characteristics, we found no pressure effect on the saturated current, and thus on the ion-production rate, for the lean and stoichiometric mixture, whereas we found
that the rich premixed flames’ saturated currents were significantly affected by the pressure. Using theoretical approach to support the results, we explained the experimentally obtained $V$-$I$ trends for the lean and stoichiometric cases, suggesting a general relationship between the current and pressure, the applied voltage, and the mass flow rate of methane. We found that the $V$-$I$ response was predictable for an arbitrary pressure condition.

We found that an increase in pressure supported the generation of ionic wind, based on PIV measurements. We observed a drastic separation in the burnt flow leading to downward entrainment, similar to the previously observed counterflow system where $V_{DC}$ belonged to the saturation regime. The effective mass transport due to the ionic wind was facilitated as the pressure increased, which was evidenced by the increased maximum transport of mass and the enlarged region of the effect. We expected that higher pressure can further enhance the degree of ionic wind, since the maximum applicable voltage preventing electrical breakdown also increases.

However, detailed investigations should be carried out in future studies that particularly consider the pressure dependence of the ion-production rate in rich premixed flames and the three-dimensional nature of the flow field in the present configuration including the separation of burnt flow.

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