Effects of AC Electric Field on Small Laminar Nonpremixed Flames

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ABSTRACT

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Electric field can be a viable method in controlling various combustion properties. Comparing to traditional actuators, an application of electric field requires very small power consumption. Especially, alternating current (AC) has received attention recently, since it could modulate flames appreciably even for the cases when direct current (DC) has minimal effects. In this study, the effect of AC electric fields on small coflow diffusion flames is focused with applications of various laser diagnostic techniques.

Flow characteristics of baseline diffusion flames, which corresponds to stationary small coflow diffusion flames when electric field is not applied, were firstly investigated with a particular focus on the flow field in near-nozzle region with the buoyancy force exerted on fuels due to density differences among fuel, ambient air, and burnt gas. The result showed that the buoyancy force exerted on the fuel as well as on burnt gas significantly distorted the near-nozzle flow-fields. In the fuels with densities heavier than air, recirculation zones were formed very close to the nozzle exit. Nozzle heating effect influenced this near-nozzle flow-field particularly among lighter fuels. Numerical simulations were also conducted and the results showed that a fuel inlet boundary condition with a fully developed velocity profile for cases with long fuel tubes should
be specified inside the fuel tube to obtain satisfactory agreement in both the flow and temperature fields with those from experiment.

With sub-critical AC applied to the baseline flames, particle image velocimetry (PIV), light scattering, laser-induced incandescence (LII), and laser-induced fluorescence (LIF) techniques were adopted to identify the flow field and the structures of OH, polycyclic aromatic hydrocarbons (PAHs), soot zone. Under certain AC conditions of applied voltage and frequency, the distribution of PAHs and the flow field near the nozzle exit were drastically altered from the baseline case, leading to the formation of toroidal vortices. Increased residence time and heat recirculation inside the vortex resulted in appreciable formation of PAHs and soot near the nozzle exit. Decreased residence time along the jet axis through flow acceleration by the vortex led to a reduction in the soot volume fraction in the downstream sooting zone. Electromagnetic force generated by AC was proposed as a viable mechanism for the formation of the toroidal vortex.

By varying applied AC in a wide range of frequency and voltage, several instability modes were observed, including flicking flames, partial pinch-off of flames, and spinning flames. High speed imaging together with Mie scattering techniques were combined to reveal the flame dynamics as well as the flow structure inside the flames. Original steady toroidal vortices triggered by AC were noted to exhibit axisymmetric axial instability in the flicking and partial pinch-off modes and non-axisymmetric azimuthal instability in the spinning mode. Electrical measurements were also conducted simultaneously to identify the voltage, current, and electrical power responses. Integrated power was noted to be sensitive to indicate subtle variation of flames properties and to the occurrence of axial instability.

Under low frequency AC forcing with electrical conditions not generating toroidal vortices, responses of flames were further investigated. Several nonlinear flame responses, including frequency doubling and tripling phenomena, were identified. Spec-
tral analysis revealed that such nonlinear responses were attributed to the combined effects of triggering buoyancy-induced oscillation of the flame as well as the Lorenz force generated by applying AC. Phase delay behaviors between the applied voltage and the heat release rate (or flame size) were also studied to explore the potential of applying AC in controlling flame instability. It was found that the phase delay had large variations for AC frequency smaller than 80 Hz and became saturated at over 80 Hz, which has been explained based on the interaction between the buoyancy and ionic wind. Electrical measurement showed the power consumed by the AC was smaller than 0.01% of the heat release rate from the flame.

To improve the understanding on the electric current resulting from applying electric field on flames, a simplified one-dimensional model was developed in that the reaction zone was modeled as a thin ionized layer. Model governing equations were derived from species equations by implementing mobility differences depending on the type of charged particles, especially between ions and electrons. The result showed that the sub-saturated current along with field intensity was significantly influenced by the polarity of DC due to the combined effect of non-equal mobility of charged particles as well as the position of the ionized layer in a gap relative to two electrodes. Experiments with quasi-one-dimensional flames under DC were conducted to substantiate the model and measured currents agreed qualitatively well with the model predictions.
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Chapter 1

Introduction

Hydrocarbon fuels will play the prevailing role as global energy source at least in the foreseeable future. Minimizing pollutant emission and increasing combustion efficiency when burning hydrocarbon fuels is two important targets in combustion research. This requires further improved understanding in fundamental aspects of combustion behavior, including chemical kinetics, soot formation and combustion instability, and also in practical aspects, including the design of active control systems.

Along with continuous improvement in combustion systems, a new concept for combustion systems is required to be investigated. Electric field assisted combustion can be a viable option in improving combustion efficiency and control of flames. Flames are under weakly ionized plasma states, since charged particles (mainly $CH_3^+$, $H_3O^+$, $HCO^+$, $C_3H_3^+$, and electrons) are generated in a reaction zone through chemi-ionization and subsequent ion chemistry [1,6,7].

Under external electric field, these charged particles can be accelerated by the Lorentz force. The accelerated charged particles transfer momentum to neutral molecules by collision, which results in a generation of bulk flow of the ionic wind [9]. Acceleration and collision of charged particles could result in a drift velocity, which could enhance diffusion flux [10] and kinetic energy gain by the acceleration could influence reaction rates associated with charged particles.

The objective of present study is to investigate the response of nonpremixed jet
flames under the influence of external electric field, especially with alternated current (AC). Various flow modulation, flame instability, and electrical responses of flames will be reported. Such information can be utilized in the future as a viable control method using electric fields.

1.1 Electric Field Assisted Combustion

William Gilbert noted that a flame could discharge an electroscope in 1600s [5]. Since then, numerous research efforts have been given in the field of electric field assisted combustion, especially focused on electrical properties of flames and responses of flames to applied electric field for potential application to practical combustion systems.

1.1.1 Electrical Properties of Flames

Concerning the electrical properties of flames, a historic timetable, based on the one by Papac et al. [4] with slight modification, is provided in Table 1.1:

<table>
<thead>
<tr>
<th>Year</th>
<th>Milestone Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>1600</td>
<td>Flame discharged and electroscope [5]</td>
</tr>
<tr>
<td>1801</td>
<td>Flame has measurable electric potential [11]</td>
</tr>
<tr>
<td>1814</td>
<td>Flame was directed to charged electrode [12]</td>
</tr>
<tr>
<td>1882</td>
<td>Flame conductivity was induced by ion movement inside [13]</td>
</tr>
<tr>
<td>1897</td>
<td>First mass spectrometry result [14]</td>
</tr>
<tr>
<td>1912</td>
<td>Voltage distribution within a flame was measured [15]</td>
</tr>
<tr>
<td>1924</td>
<td>Invention of Langmuir probe [5]</td>
</tr>
<tr>
<td>1961</td>
<td>Identification of dominant chemi-ionization reactions [16]</td>
</tr>
<tr>
<td>1979</td>
<td>Ion chemistry for both anions and cations [6,7]</td>
</tr>
<tr>
<td>1997</td>
<td>Detailed review paper on ions in flames [1]</td>
</tr>
</tbody>
</table>

Lawton and Weinberg in 1969 summarized possible approaches resulting in the ionization in a flame as shown in Table 1.2:
Table 1.2: Summered Possible Ionization Approaches

<table>
<thead>
<tr>
<th>Ionization Mechanisms</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionization by collision</td>
<td>( A + B \rightarrow C^+ + D + e^- )</td>
</tr>
<tr>
<td>Electron transfer</td>
<td>( A + e^- \rightarrow A^+ + e^- + e^- ) ( A + B \rightarrow A^+ + B^- )</td>
</tr>
<tr>
<td>Excitation energy transfer</td>
<td>( A + B^* \rightarrow A^+ + B + e^- ) ( A + B \rightarrow C^+ + D^- )</td>
</tr>
<tr>
<td>Chemi-ionization</td>
<td>( A + B \rightarrow C^+ + D + e^- ) ( A + B \rightarrow C^+ + D^- )</td>
</tr>
<tr>
<td>Thermal ionization</td>
<td>( A \leftrightarrow A^+ + e^- )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electron Attachment Mechanisms</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiative attachment</td>
<td>( e^- + A \rightarrow A^- + h\nu )</td>
</tr>
<tr>
<td>Three-body attachment</td>
<td>( e^- + A + X \rightarrow A^- + X ) ( (A^*)^- + X \rightarrow A^- + X )</td>
</tr>
<tr>
<td>Dissociative attachment</td>
<td>( AB + e^- \rightarrow A + B^- )</td>
</tr>
</tbody>
</table>

In the ionization mechanisms, the collision induced ionization is a process that the kinetic energy of one molecule is transferred to the outer orbit electron of the other molecule during the collision process, through which the electron gains enough energy to escape from the parent molecule. By comparing ionization efficiency induced by different particles \[17, 18\], only electrons of the temperature ranging from 0.1-1 eV were efficient in inducing ionizations in a flame zone via collisions \[5\]. The electron transfer induced ionization is an endothermic process and can be important especially when certain material is added in the flow stream of reactants \[5\]. Ionization could also occur during the transfer of excitation energy, especially when the reaction is thermoneutral \[17, 19\].

The chemi-ionization is a process that ionization of product species occurs due to the energy release during chemical elements rearrangement. For solid particles within a flame, thermal energy induced ionization, known as the thermo-ionization, can be described according to the Saha equation \[1\],

\[
\frac{n_+ n_e}{n_A} = G(M_e \frac{2\pi kT}{h^2})^{3/2} \exp\left(-\frac{A_I}{kT}\right),
\] (1.1)
or in the log form as,

\[
\ln\left(\frac{n_+n_e}{n_A}\right) = -\frac{5050}{T} A_I + 1.51 g + 15.37 + \ln G,
\]  

(1.2)

with \( G = \frac{\omega_i + \omega_e}{\omega} \). Inside \( \omega \) is the statistical weight \[1\]. Here \( n_+, n_e \) and \( n_A, (M_+, M_e, M) \) are the concentrations (molecule masses) of positively charged particles, electrons and neutral particles, respectively, and \( k, T, h \) are Boltzmann constant, temperature, and Planks constant of the species, respectively. \( A_I \), the ionization potential \( A_I \) of species can be evaluated via \[1\][20]:

\[
A_I = A_W + \frac{e^2}{2C},
\]  

(1.3)

where \( A_W \) is the work function of the material consisting that specie, \( e \) is the elementary charge and \( C \) is the capacity of species depending strongly on particle geometry.

Concerning the electron attachment mechanisms, the radiative attachment is a relatively show process thus not likely to occur in a flame zone. The three body attachment is suspected to be important in a flame at high pressure \[1\]. The dissociative attachment occurs when electrons are energetic enough to break the chemical bond of molecules and attached to one of the product such as:

\[
O_2 + e^- \rightarrow O + O^-.
\]  

(1.4)

In nonpremixed flames, the flame front is located near the stoichiometric contour \[21\]. In addition, soot formation is more susceptible as compared with premixed flames. Thus, most important ionization mechanisms as well as produced ions in near stoichiometric and sooting flames will be discussed.

For nearly stoichiometric premixed flames, the peak of positive ion concentration occurs near the chemi-luminescence zone as shown in Fig. \[1\] \[1\]. Chemi-ionization
within this region, widely accepted as the main source of ions of hydrocarbon flames, can explain observed ion concentration peak.

Figure 1.1: Profiles of concentration of positive ions in propane/air flat flames at various equivalence ratios and pressures [1].

Calcote et al. [16] first proposed the dominant pathway of chemi-ionization as:

$$CH + O \rightarrow HCO^+ + e^-,$$  \hspace{1cm} (1.5)

which was confirmed later by Gardner et al. [22]. In addition, Knewstabb and Sugden [23] proposed the following important chemi-ionization reaction,

$$CH^* + C_2H_2 \rightarrow C_3H_3^+ + e^-,$$  \hspace{1cm} (1.6)
where $C_3H_3^+$ was noted to peak near a flame front especially for rich flames.

To validate the impact due to the excitation of $CH$ radicals, a dedicated experiment was designed by Calcote et al. [24] via adding carbon dioxide into acetylene-oxygen premixed flame. Since $CH^*$ could be removed efficiently via $CO_2$, a significant decrease in the concentration of $C_3H_3^+$ could be expected. The experimental result showed that the concentration of $C_3H_3^+$ decreased 10 times faster than $HCO^+$ by adding $CO_2$ thus validating the assumed reaction pathways [1]. Experiments supporting the importance of these two reactions could also be found in [25–28]. The exception was that the work of Cool and Tjossem [29] supported the importance of $CH^*$ in producing $HCO^+$.

After the identification of the key chemi-ionization reactions, later efforts have been focused in developing detailed ion chemistry [1, 6, 7]. Typical chemical pathways in non-sooting methane flames to convert $HCO^+$ and electrons to positive and negative ions are shown in Fig. 1.6 according to Prager et al. [2],

![Diagram of ionic reactions](image)

Figure 1.2: Pathways of ionic reactions for cations and anions from Prager et al. [2].

Similar ion chemistry for methane/air mixture could also be found in other works
Table 1.3: Important charged particles from literatures [1,6–8]

<table>
<thead>
<tr>
<th>Cations</th>
<th>HCO$^+$, H$_3$O$^+$, C$_3$H$_3^+$, CH$_3^+$, CH$_5$O$^+$, C$_2$H$_3$O$^+$, C$_2$H$_5$O$^+$, CH$_3$O$_2^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anions</td>
<td>e$^-$, O$_2^-$, OH$^-$, C$_2^-$, C$_2$H$^-$, O$^-$, CO$_3^-$, HO$_2^-$, O$_3^-$, CHO$_2^-$, CHO$_3^-$</td>
</tr>
</tbody>
</table>

$C_3H_3^+$ not appeared in Fig. 1.6 since it was usually accepted as a secondary ions unless in acetylene flame [8,33].

H$_3$O$^+$ has been supported to be the most abundant ions especially verified in methane/air mixture [8,34]. This is because owing to the abundant concentration of H$_2$O produced during combustion, following conversion reaction takes place [8,16,34],

$$HCO^+ + H_2O \rightarrow CO + H_3O.$$  \hfill (1.7)

Moreover, H$_3$O$^+$ could convert to other cations, shown also in Fig. 1.6 via [2,34]

$$H_3O^+ + B \rightarrow C^+ + D.$$  \hfill (1.8)

In terms of anions, electrons were noted to be the most dominant negative charge carrier [24]. As regards, most simulations usually neglect negative ions for simplicity [8,31,34]. The attachment of electron to oxygen was accepted as the most important reaction path to form negative ions especially near the low temperature region [7,34,35] as:

$$O_2 + e^- + M \rightarrow O_2^- + M.$$  \hfill (1.9)

The list of typical abundant positive and negative particles in non-sooting flames is shown in Table 1.3. Related detailed ion chemistry could be found in Goodings et al. [6,7] and Prager et al. [2].

As fuel-air mixture becomes richer, the formations of polycyclic aromatic hydrocarbons (PAHs) and soot becomes appreciable (here the definition of PAHs also includes one ring structure). Details regarding the growth and decay of PAH ions
and transition to solid soot particles are not fully resolved. It is generally accepted that $C_3H_3^+$ is acting as seeds for the ions formation of light aromatics via:

$$C_3H_3^+ + C_6H_6 \rightarrow C_7H_7^+ + C_2H_2.$$  

(1.10)

The size of light PAH ions grows to a bigger one such as $C_{13}H_9^+$ and $C_{13}H_{11}^+$ via adding building-blocks neutrals such as $C_2H_2$ and $C_4H_2$. Experimentally, it was observed that heavier PAHs exist farther downstream from a flame in the McKenna burner configuration. There are also views that larger PAH ions could from direction reaction between $C_3H_3^+$ and neutral PAHs via charge-exchange reactions [1]. Reaction (1.10) can successfully explain maximum PAH concentrations near a reaction zone due to high concentration of $C_3H_3^+$ locally. Experimentally, another local peak also appears near a sooting region, but the peak concentration is usually smaller as compared with the first [1]. Soot particles of large size can be charged due to thermo-ionization since associated work function is usually low (about 5 eV) [36]. Small size soot particles and large gaseous molecules such as PAHs and fullerenes with mass around several thousands amu can hardly be ionized thermally due to their high ionization potential [37]. Thermo-ionization point of view relies on the comparison between charged particle concentration with the one predicted by Saha equation, which requires the electron number density and working function of soot particles in advance, while proper values for these two parameters are still unclear. Due to the highly nonlinearity of Saha equation, uncertainty of the prediction is quite large thus not convincing as pointed out by Homann et al. [38] and Fialkov et al. [1].

Regarding the source of ions accompanying soot formation, there are generally two explanations. One is the thermo-ionization of solid soot particles for charged solid particles in a sooting region and the other is charged gaseous PAH ions, the precursor of soot, which go through cyclization, coalescent coagulation, surface attachment and
soot inception processes and form charged soot particles finally [39].

Most up-to-date point of view is that both the thermo-ionization and chemi-ionization contribute to high ion concentration in sooting region. The importance of chemi-ionization is confirmed since even before a flame becomes sooting, the ion concentrations already start to rises and the appearance of PAH ions could also be identified simultaneously [40][42]. In fact, Calcote et al. [43] found that the peak total ion concentrations in sooting flames occurred in the upstream of soot formation region, while in a sooting region, the charged soot number density distributions matched the one of neutral particles indicating the role of thermo-ionization there. Obviously, the ionization process is undergone for soot precursors via chemi-ionization ahead of the formation of soot particles large enough to be thermally ionized.

Owing to the existence of small gaseous ions, PAH ions as well as charged soot particles in flames, it is possible to utilize the electrical nature of flame to achieve either diagnostic or controlling purpose over combustion processes, which will be discussed in the following.

1.1.2 Utilization of Electrical Nature of Flames

There are mainly two directions in utilizing the electrical nature of flames. One is to build ionization probe type of sensors based on the correlation, usually empirical, between ion currents and flame parameters. In this case, external electric field is applied only for diagnostic purpose, thus the magnitude of the field is usually limited to avoid perturbing the flames. The other direction is to utilize electric field as an actuator in modulating a flame. In this case, applied electric field must be strong enough to induce observable effects. In the following, we will briefly introduce up-to-date achievements in both directions.

- **Sensors.** Ionization probe is to detect current in a flame zone. Main motivation in designing or applying an ionization probe can be attributed to its simplicity
and in-situ measurement ability [44]. There are several commercialized ion sensors in the market. Simplest one is to indicate the existence of hydrocarbon flames, when ion current can be detected. This type of sensors are usually adopted for small scale burners such as gas appliances [45]. To improve the current detection sensitivity, external power source of AC is usually integrated with the sensor instead of DC by utilizing flame rectification effect [46, 47]. Further efforts were made to correlate the current with peak pressure [48, 49] and equivalence ratio control [50, 51].

In spark ignition engines, the ignition circuit of spark plug can be modified slightly to allow an ion current measurement after ignition. A relationship can be determined between measured current and engine parameters such as, crank angle, air-fuel equivalence ratio [52], misfire [53], and knocking [54, 55]. However, it has also been noted that ion current signals relied on too many engine parameters thus building a proper one-to-one correlation with a certain flame parameter was difficult [44].

Ionization detectors are also designed to use under less turbulent conditions. For example, when integrated with a gas chromatography as the role of detectors, gas species concentrations (especially for hydrocarbons) could be easily determined by measuring the saturation ion current resulted from burning the species in a small hydrogen flame [56, 57]. It can also work independently in monitoring fugitive emissions or exhaust gas in the post section of internal combustion engines [57, 58]. In laboratory scale flames, as summarized by previous reviews [1, 45, 59], ionization induced currents could be correlate with flame quenching state, reaction intensities, locations of flame fronts, and even chemiluminescence and acoustic fluctuation in turbulence flames.

- **Actuator.** After applying electric fields, charged particles generated via chemi-
ionization can be accelerated by the Lorentz force when electric field is applied. Various observed flame responses can be attributed to four potential mechanisms: 1) Chattock wind or ionic wind effect [9], due to which a flow bulk motion can be induced via the momentum transfer by the collisions between accelerated charged particles and neutral molecules. 2) modified transport properties of charged species such as drift velocity [10]. 3) altered chemical kinetics [60] by gained kinetic energy of accelerated charged particles. 4) ohmic heating, which is usually accepted to be negligible since the power consumption during the electric field assisted combustion is in the order of 1 W or less. For premixed flames, both transport properties and reaction rates affect flame propagation characteristics, separation of these two effects from flame responses is often difficult.

Among these mechanisms, ionic wind is relatively well understood and widely adopted in explaining observed flame behaviours. In table 1.4, recent important research works are summarized in using electric fields as an actuator to control flame properties. It covers the utilization of AC or DC on premixed and non-premixed flames, resulting in the modulations on propagation speed, limited phenomenon, flow structure, soot and pollutant, and instability.
Table 1.4: Selected Research Works in Electric Field Assisted Combustion.

<table>
<thead>
<tr>
<th>Flame properties</th>
<th>DC or pulsed DC</th>
<th>AC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Premixed or Lifted Flame</td>
<td>Non-premixed Flame</td>
</tr>
<tr>
<td>Propagation</td>
<td>Lewis et al. [61], Blair et al. [62], Jaggers et al. [63], Bowser et al. [64], Fowler et al. [65], Noorani et al. [66], Vega et al. [67], Boom et al. [68], Mario et al. [69], Marcum et al. [10], Won et al. [70, 71]</td>
<td>Sher et al. [78, 79], Belhi et al. [84, 80], Cessou et al. [81]</td>
</tr>
<tr>
<td>Blowoff, extinction, lift-off</td>
<td>Calcote et al. [75], Noorani et al. [76], Ata et al. [77]</td>
<td>Kim et al. [74, 82, 83], Won et al. [70]</td>
</tr>
<tr>
<td>Flow structure</td>
<td>Altendorfner et al. [85], Kuhl et al. [86], Tretyakov et al. [87]</td>
<td>Lawton et al. [88], Carleton et al. [89], Strayer et al. [90], Papac et al. [4], Rankin et al. [91]</td>
</tr>
<tr>
<td>Pollutants</td>
<td>Zake et al. [93], Sakhrieh et al. [94], Vega et al. [95], Wang et al. [96]</td>
<td>Mayo et al. [97], Xie et al. [98], Daeguen et al. [99], Saito et al. [100, 101]</td>
</tr>
<tr>
<td>Instabilities modulation</td>
<td>Volkov et al. [103], Kuhl et al. [104], Schmit et al. [105, 106]</td>
<td></td>
</tr>
</tbody>
</table>
1.2 Nonpremixed Jet Flames

Nonpremixed jet flames are widely adopted in many practical combustors, such as diesel engines, turbines, and furnaces. A safety consideration can be a one reason since flashback-induced explosion hazard often occurs in premixed flames, can be excluded. Facilitated with coflow air stream, mixing processes between reactants are augmented, which could results in enhanced combustion efficiencies and reduced flame size allowing compact combustion chambers [108].

Experiments conducted under microgravity environment either in drop towers or in space shuttles have verified the importance of buoyancy effects on nonpremixed jet flames related to instabilities [109–113], mixing efficiency [89], radiation heat transfer [114], flame shapes [115] and soot formations [116–118]. Under the normal gravity, strong buoyancy is always exerted in nonpremixed jet flames due to significantly reduced gas density near flame front.

A buoyancy effect can alter the instability of nonpremixed jet flames. Flicking flares, such as firewood dancing fire in a furnace or candle flames, are frequently encountered buoyancy-driven unstable flames. Numerous efforts have been given to identify mechanisms responsible for flickering flames. Pioneering works on this phenomenon based on a well defined laboratory jet burner were given by Chamberlain et al. [119,120], and a flickering frequency in the range of 10 to 20 Hz was reported. Later, optical diagnostics, numerical simulations and analyses have been conducted. As summarized in [121], flow structures of flickering flame depends on the jet Froude number, defined as \( Fr = \frac{U_{jet}^2}{gD} \), where \( U_{jet} \) is the fuel jet velocity, \( g \) is the gravity acceleration and \( D \) is the inner diameter of jet nozzle.

Visualization of flame structures at several \( Fr \) by adopting reactive Mie scattering is shown in Fig. 1.3, where the outermost and innermost green regions are from Mie scattering of \( TiO_2 \) particles generated by the reaction between \( TiCl_4 \) and water vapor, and yellow and blue flame zone can also be identified. For large \( Fr \) case (a),
the shear layer instability occurs inside the flame zone toward the fuel side, while the flame corrugation especially in the upstream region is relatively small.

For high Fr cases, buoyancy effect is relatively small as compared with jet momentum, thus buoyancy-induced instability can be secondary. Shear layer instability can be initiated near a flame base and facilitate the flow transition from laminar to turbulent flow in the downstream.

As Fr decreases (b-d), the contribution by buoyancy-driven instability becomes conspicuous in the form of large-size vortical structures. Toroidal vortices are generated near the nozzle. As travelling downstream, the amplitude grows resulting in the formation of flame bulge, having a rapid increase in the flame radius, through which flame stretch and mixing can be enhanced [3]. The typical frequency is in the range of 10-20 Hz.

For further decreased Fr, the amplitude of vortical structure and thereby stretch effect becomes strong enough near the flame tip region, part of the flame is detached from the main flame, known as flame pinch-off [122, 125] phenomenon (d). For very small Fr, buoyancy induced visible vortical structure vanishes and only flame tip might exhibit small amplitude oscillation motions (e).
Shear layer instability in the fuel side is well understood [126]. The origin of vortical structures observable by naked eyes in the form of flame bulge in the coflow side has been under debates since 1960s. The first and most lasting explanation was attributed to the acceleration of burnt gas by buoyancy along with the acceleration of fuel region by buoyancy-induced entrainment. This generated large velocity difference between products (and fuel) and ambient coflow air, resulting in the modified Kelvin-Helmholtz instability [126–129]. This mechanism was further supported by the analog study under a non-reacting jet with large density differences between the injection gas and surrounding coflow air stream [129].

However, experimental observations showed that small perturbations did not affect the flicking frequency nor flame structures. Besides, flickering motions acted more like self excitations, indicating the instability was driven by absolutely unstable flows instead of convective unstable one [130–132]. Recent series of works of Luo el al. [133–135], by simulating each source and sink term within vorticity transport equation, confirmed that the origin of vorticity generation in flickering nonpremixed flame was from the interaction between the radial density gradients and gravity during the initial
stage of vortical structure formation and magnified by the baroclinic torque due to the misalignment between pressure gradient and density gradient along the flame surface downstream.

Difficulties was also encountered in explaining the existence of stable or slight tip flickering flames under very small $Fr$ (e.g., Fig. 1.3 e). In such a case, vortical structure of flame disappears while misalignment between gravity and density gradient still exists. No specific mechanism should prevent the onset of vortical structures in this case according to the explanations by Kuo et al. Boulanger et al. noted that slightly flickering flame tip and shedding vortices shared the same instability due to similar spectral density of the probed velocity signals. But further analysis on the vorticity budget showed that the vorticity expansion and stretch effects could minimize the vorticity creation along the flame surface such that the net source of vorticity downstream was not sufficient to sustain the varicose structures.

The baseline flame in this study without applying electric field is a stable flame similar to the one shown in Fig. 1.3 e. To distinguish the flow field modulation induced by electric field, baseline flow structures need to be clarified first. As will be shown in Chapter 5, AC electric field could trigger flickering flames. Understanding the mechanism for flame flicker without electric field can shed a light in understanding electric field triggered flickering instability.

1.3 Objective

Main objectives of this study are as follows:

- Investigation of the flow structure of small laminar jet flame; Since the baseline flame without applying electric fields is a small nonpremixed jet flame, understanding associated flow structure is important to distinguish the impact from AC electric fields over the flow structure from the original one. Although there have been numer-
ous studies in revealing jet flame structures, their attentions were mainly limited to moderate or high Reynolds number conditions. We will focus on the flow structure in small jet flames by considering the fuel density and nozzle heating effects with laser diagnostic techniques including Mie scattering and particle image velocimetry (PIV).

- Testing the flame response under applied AC electric fields. According to the literature summary Table 1.4, it can be noted that effects of AC electric fields over flame instability has received limited attentions. In this regard, this thesis will study the interaction between AC and small laminar nonpremixed jet flames within a wide range of voltage and frequency. As will be shown in Chapter 4, AC electric field is capable to trigger an inner toroidal vortices in the near nozzle flow field. By varying frequency and voltage, both flame flickering and spinning instability can be triggered from the baseline flame as shown in Chapter 5.

- Applying comprehensive laser diagnostic techniques in electric field assisted combustion. Previously, in the field of electric field assisted combustion, laser diagnostics were rarely adopted in a systematic way. This might results in inaccurate conclusions. For example, without studying the flow field and PAHs concentrations, it is difficult to explain why electric field affected soot concentration. As such, this thesis will combine Mie scattering, planar laser induced fluorescence, planar laser induced incandescence and high speed particle image velocimetry together to determined associated OH, PAHs, soot volume fraction and velocity fields to draw a detailed picture describing the impact from AC over baseline flames as shown in Chapter 4.

- Correlating the flame dynamics with the electrical signals resulting from the AC electric fields. When utilizing the electrical nature of flame to design a sensor, an additional power source is usually required to provide small electric fields under which flames are assumed to be unperturbed. When external electric field is utilized as the actuator, ion current is produced as byproduct. How to use this actuating induced current is of special interest to design a feedback control system based on
only one power source. In this thesis, we will shed the first light on the possibility to implement this idea under AC condition as shown in Chapter 5 and 6.

- Understanding the electrical current behavior within electric field assisted combustion. Electrical current is the most widely used electrical signal to be correlated with flame parameters in commercial sensors thus how to understand the current behaviors provide insight over existing ionization type sensors and motivate a better design. There are only limited attempts to predict the currents behaviors under electric fields and most of them are based on detailed ion chemistry while the determination of ion chemistry reaction rate constant is a problem itself. In this thesis, we will propose a much simplified mathematical model to predict the ion current behaviors. A phenomenon puzzled the community for a long time, called current diode effect, is clearly explained from this simplified model.

1.4 Dissertation Organization

The thesis is organized as following:

- In chapter 2, experimental techniques adopted in the dissertation were summarized.

- In chapter 3, the flow structure of a small laminar diffusion jet flame was investigated with special focus on the fuel density effect and nozzle heating effect. The materials within this chapter have been published as: Y. Xiong, M.S. Cha and S.H. Chung, "Fuel density effect on near nozzle flow field in small laminar coflow diffusion flames", Proceedings of the Combustion Institute, Vol. 35, 873-880, 2015.

- In chapter 4, special vortical structures induced under AC electric field were revealed under various laser diagnostic techniques. The materials within this chapter have been published as: Y. Xiong, M.S. Cha and S.H. Chung, "AC electric field induced vortex in laminar coflow diffusion flames", Proceedings of the Combustion
In chapter 5, new instability modes of small diffusion flame under AC electric fields were reported. The materials are under preparation for submission and the paper information will be as following: Y. Xiong, M.S. Cha and S.H. Chung, ”Instabilities and Electrical Responses of Small Laminar Coflow Diffusion Flames under AC Electric Fields”.

In chapter 6, a special focus has been given to the flame dynamical response under very low AC frequency. The highly nonlinear flame responses were revealed to relate to the strong buoyancy experienced by the flame. The material is under preparation for submission and the paper information will be as following: Y. Xiong, M.S. Cha and S.H. Chung, ”Buoyant Flame Responses under Low Frequency AC Electric Fields Forcing”.

In chapter 7, an one dimensional numerical model has been developed to improve the understanding of the current behaviours of flames under external electric field. Well known current diode effect can be successfully explained based on this code. Within this chapter, the experimental data utilized for comparison purpose was from Daegeun Park. The material is under preparation for submission and the paper information will be as following: Y. Xiong, D.G. Park, B.J. Lee, S.H. Chung and M.S. Cha, ”Electrical current with a thin ionized layer: effects of relative position and mobility of charged particle”.

In chapter 8, summary of the dissertation was made and future works were also discussed.
Chapter 2

Experimental Setup

2.1 Introduction

Most of the experiments in this study adopted an axisymmetric coflow burner based on the ones used previously [83, 136]. Several modifications were made for different sizes of coflow honeycombs, fuel nozzle diameters, and electrode gap distances. A shroud compatible with both optical and electrical diagnostics has also been used. Details of the burner system can be found in Appendix 1.

Various types of laser diagnostic techniques, including Mie scattering, planar laser-induced fluorescence (LIF), planar laser-induced incandescence (LII), and particle image velocimetry (PIV) have been adopted. An improved system to measure electrical signals was implemented, which was synchronized with the optical diagnostic systems for flames under alternating current (AC) electric fields.

2.2 Coflow Burner

The coflow burner consisted of a central fuel nozzle and a concentric coflow air nozzle. The fuel nozzle was a stainless steel tube with flush end having the inner (outer) diameter of the tube of 10.8 (12.8) mm. The length of the nozzle was 855 mm, long enough to allow the flow to be fully developed in the laminar regime. The coflow
air was passed through plastic beads and a ceramic honeycomb (400 cells per square inch) for the flow to be reasonably uniform. The diameter of the ceramic honeycomb was 150 mm, large enough to shield disturbances from the surrounding.

In applying electric field, the fuel tube served as the high voltage electrode and a fine stainless mesh served as the ground, which had the same diameter as the coflow honeycomb, placed 27 cm above the fuel nozzle. Since the electrodes temperature was not controlled externally and to maintain a similar electrode temperature among all tests, the baseline flame without applying electric fields was operated for about 10 min before applying electric field to reach a reasonable thermal equilibrium state.

The adoption of the shroud was advantageous for two reasons. First, it could provide well-defined boundary conditions for computation. Second, when AC electric field was applied, electric current response could be easily measured at the ground electrode side embedded within the shroud. In order to allow a laser beam passing through the shroud, quartz windows (6 mm in thickness) with optical grade purity were installed on four sides of the shroud. Under certain circumstances, the shroud was removed, e.g., to test nozzle heating effect (Chapter 3) or for tomographic imaging (Chapter 4 not involving current measurement). The axis symmetry of flame was found to be extremely sensitive to the flow field near the nozzle, which depended on joint region between the ceramic honeycomb and the fuel tube.

2.3 High Speed Imaging

Under AC electric fields, flames could exhibit oscillatory motions. To capture the transient dynamics of flames, high speed imaging is required. Two high speed cameras (Photron MC2 and SA4) were utilized. When the light intensity was weak, MC2 camera (gray scale, up to 2000 fps with 512 \times 512 resolution) was used (f = 1.6), which was also coupled with a continuous wave laser to implement PIV measurements.
For a higher framing rate, SA4 was utilized (color, up to 22000 fps with 512 × 512 resolution) which allowed long recording time, such that frequency spectra of flame dynamics can be extracted.

2.4 Mie Scattering

When particle size is similar or larger than the wavelength of incident light, photons will be scattered with the same frequency as the incoming light and the Mie theory can be applied. The scattering behaviour is mainly determined by the normalized diameter $q$ of particle defined as [137]:

$$ q = \frac{\pi d_p}{\lambda}, \quad (2.1) $$

where $d_p$ is the particle diameter and $\lambda$ is the wavelength of incident light. For velocity measurement, $TiO_2$ particles were seeded (1 $\mu m$ nominal diameter). Mie scattering images were captured at 90° from the laser beam direction. An illustrative setup, as schematically shown in Fig. 2.1 consisted of an Ar-ion laser (Spectra-Physics, Stabilite2017 at 488 nm) and a high speed imaging system.
Figure 2.1: Experimental setup for Mie scattering imaging with particle seeding.

Although the dominant scattering signals were from seeded TiO$_2$ particles, for sooting flames, laser-induced fluorescence signals from polycyclic aromatic hydrocarbons (PAHs) and Mie scattering signals from small size soot particles could also be captured. Details on laser-induced fluorescence will be discussed later.

Considering that the sizes of soot particles were much smaller than the laser wavelength, the Rayleigh scattering theory can be applied, where the scattering intensity depends mainly on particle diameter. These signals could be effectively separated in nonpremixed jet flames seeded particles to the fuel stream mainly followed fuel streamlines while soot particles and PAHs are located in a diffusion zone.

2.5 Laser-Induced Fluorescence (LIF)

During the molecule transition from excited to ground states, photons are emitted by the energy difference between two states. When molecules are excited via incident
laser source, subsequent spontaneous emissions of radiations are termed as laser-induced fluorescence (LIF). Since the energy required to excite molecules is typically high, pulsed lasers are usually adopted. In this study, OH and PAHs were investigated qualitatively by adopting LIF techniques.

The planar LIF setup, as schematically shown in Fig. 2.2, consisted of a Nd:YAG laser (Continuum, Powerlite DLS), a dye laser (Continuum, ND6000), and a frequency doubler (Continuum, UVT). OH radicals (excited at 282.96 nm) and PAHs (excited at 283.00 nm) were measured using the PLIF setup with an intensified charge-couple device (ICCD) camera (Princeton Instruments, PI-MAX3 1024i) with a set of UG 11 and WG 305 filters [139]. Forty images were accumulated with a correction for background noise.

![Figure 2.2: Experimental setup of PLIF system.](image)

The baseline flame height was 4.3 cm and a relatively wide laser sheet beam was used. Since the laser light was nearly Gaussian, non-uniformity of the beam intensity also appeared. To compensate this, the laser beam intensity was first calibrated using
the excitation signals from acetone contained in a cuvette, accordingly OH or PAHs signals. For the detection of PAH signals, a band pass filter (305 - 400 nm) was used, which corresponded to a large size group of PAHs [138]. A time delay generator was used to synchronize the Nd:YAG laser with the ICCD camera, having the gate width of 200 ns and the recording was triggered by laser pulse.

2.6 Laser-Induced Incandescence (LII)

Incandescence is referred to thermal radiation emission from a hot surface. Laser-induced incandescence is a technique that heats soot particles via high energy laser pulse up to about 4000 K, where soot particles can have strong blackbody radiation and detects to determine reasonable soot volume fraction information [140–142].

The LII measurement setup was similar to the LIF system, as schematically shown in Fig. 2.3. A narrow band pass filter centered at 450 nm with 25 nm full width at half maximum (FWHM) was utilized to obtain saturated LII signals [141].

Figure 2.3: Experimental setup of PLII system.
Again, the Nd:YAG laser (Continuum, Powerlite DLS) was used as the light source. Typically, LII signal increases linearly with laser pulse energy and then saturated (Fig. 2.4). At further increased energy, the signal decreases by partial burn-out of soot particles. In the saturated regime, slight variation in laser energy does not affect LII signal [141].

![Laser pulse energy and associated LII signals for baseline flame.](image)

Figure 2.4: Laser pulse energy and associated LII signals for baseline flame.

To adjust the laser energy, a combination of a half wave plate and a polarized beam splitter was used. By rotating the half wave plane, the ratio of vertical polarized light passing through the beam splitter varies. Saturated LII signal was achieved for the baseline flame at about 40 mJ per pulse at 532 nm wavelength. The laser pulse and
ICCD camera were synchronized.

2.7 Particle Image Velocimetry (PIV)

Particle image velocimetry is an optical based, non-intrusive method measuring instantaneous velocity fields. In this study, two-dimensional PIV was mainly adopted to determine velocity fields.

2.7.1 Seed Particles

To guarantee the accuracy in PIV measurement, seed particles should be carefully chosen to follow the flow field well. To accurately trace flow, the velocity lag between seed particles and flow fields should be small, which can be determined from the Stokes drag law \[137\],

\[
U_s = d_p \frac{\rho_p - \rho}{18\mu} a,
\]

(2.2)

where \(U_s\) is the lag velocity between the particle and flow, \(\rho_p(\rho)\) is the particle (fluid) density, \(d_p\) is the particle diameter, \(a\) is the local acceleration, and \(\mu\) is the dynamic viscosity of the fluid. In this study, the fluid was gases and the seed particles were metal oxides such as \(TiO_2\) and \(Al_2O_3\) with high melting points to sustain high temperature. Consequently, there was large density difference. To guarantee a small velocity lag, the particle size must be very small. The particle size of \(TiO_2\) particles was about 1 \(\mu m\) to compensate the density effect. Velocity lag could be simply evaluated at the order of 0.1 \(cm/s\) thus negligible as compared with a typical flow velocity of about 10 \(cm/s\).
2.7.2 Dual-Pulse Laser and Dual Frame Camera

In PIV system, typically a dual-pulse Nd:YAG laser and a synchronized dual-frame camera have been utilized, since most post processing algorithms are based on the cross-correlation method involving two frames with a short time interval.

Depending on the repetition rate, PIV system can be either categorized as low speed (about 10 Hz) or high speed (up to kHz rate). The PIV systems adopted were low-speed PIV (Lavision, Nano PIV) and high-speed PIV (Lavision, 3D Flowmaster). For stationary flames, only low speed PIV was used. While for unsteady flames, high-speed PIV at kHz rate was used. The drawback of kHz PIV system was limited time duration for recording.

Figure 2.5: Experimental setup of low speed PIV system.
2.7.3 Continuous Wave Laser and Single-frame High Speed Camera

In this study, flame dynamics covered a wide frequency range in a relatively long time interval. It is required to obtain flow field variation synchronized with applied electric fields. In this regard, a PIV system was devised by utilizing a continuous wave laser and a single-frame high-speed camera (Photron, MC2). Advantages of this setup included the repetition rate of PIV depending only on frame rate of the high speed camera, ranging from 50 Hz to 2000 Hz. In addition, synchronizing the high speed camera with power supply system was simple.

Associated drawbacks were mainly twofold. First, the scattering light from seed particles, comparing with that with pulsed laser approach, was much weaker. Second, time interval between two frames was determined by frame rate, which was usually at millisecond level. When the flow velocity was high and lens magnification was large, seed particles could move with a large pixel distance within 1 ms, thus the cross-correlation algorithm calculating flow field may not be applicable. Thus, this technique could only be applied for low flow velocity cases. A main advantage of this system is in the freedom of selecting two frames with arbitrary time interval among a series of frames, which enables to determine low flow velocity especially in a recirculation zone. Following measures were taken to improve the performance of this approach:

- Small aperture lens was used (f=1.6).

- Sensitivity level of the CMOS chip of MC2 was increased to the highest level (level 3).

- Gain of the camera, similar to ISO in typical digital camera, was increased to the highest level (level 3).
• Velocity limitation was a barrier in this technique could not be simply avoided unless the camera frame rate was further increased. Thus, this technique was limited to the near nozzle flow fields of laminar nonpremixed jet flames where the flow velocity was very small (about 10 cm/s).

• Recording frame rate speed was always smaller than the shutter speed at least two times to better distinguish individual particle in two frames.

This technique has been validated to be consistent with the PIV based on double-pulse laser and dual-frame camera for velocities range below 30 cm/s. All the recorded images were processed via commercial software (Lavision 8.1).

2.8 Electrical Signal Measurement

Measuring electrical signals, including applied voltage, current and power consumption, is of special importance in electric field assisted combustion. Applied voltage was measured using a 1:1000 high voltage probe (Tektronics, P6015A) at the high voltage side (nozzle) and the resulting current was measured at the ground side using a current preamplifier (Stanford Research System, SR570). Note that in the literature, electric current was usually measured at the ground electrode by measuring a voltage across a known resistor. This might encounter two problems. First, to obtain a small current, a large resistor was required, such that once coupled with the cable capacitor, it might degrade the frequency response and phase accuracy of current. Second, for current source, resistive termination can possibly result in large bias voltage usually not desired. Measuring the current using the preamplifier can avoid these two problems.
2.9 Synchronizing Electrical and Optical Diagnostics

Although the research works in electric field assisted combustion were abundant, there are limited works which synchronized electrical signals with flame behavior variations. In this study, the electrical signal collection system was synchronized with the high speed camera and PIV system to provide multiple signals simultaneously including flame front dynamics, current, apply voltage, power consumption and velocity fields. This was achieved via a time delay generator sending TTL triggering signals to electrical power supply and to high speed camera separately. To compare the flame with and without applied electric fields, the high speed camera always started recording 0.5 s ahead of applying the electric fields. Such system is shown schematically in Fig. 2.6.

Figure 2.6: Experimental setup of synchronized electrical and optical diagnostic systems.
Chapter 3

Fuel Density Effect on Near Nozzle Flow Field in Small Laminar Coflow Diffusion Flames

3.1 Introduction

Small laminar coflow diffusion flames have been investigated extensively in soot studies, including a determination of the threshold soot index (TSI) for gaseous fuels [143–145]. Numerical simulations of coflow flames have been performed to validate various combustion characteristics, such as the gas-phase reaction [146], radiation [147], hydrodynamic structure [148], instability [149], and soot [116, 150]. These simulations require accurate inlet boundary conditions, particularly for the fuel stream.

In a laminar coflow diffusion flame, there is appreciable influence on the flow-field when buoyancy acts on the burnt gas region. The accelerated vertical flow velocity, leading to flame flickering motions [128, 129], highlight the role of buoyancy. The buoyancy can also affect the fuel flow. As the density of fuel becomes appreciably different from air, the near-nozzle flow-field could also be significantly influenced.
This has been demonstrated in propane jets with lifted flames by comparing cold and reacting flows \[151\].

Under a moderate Reynolds number fuel stream, the hydrodynamic structures of jet diffusion flames have been well reported \[152\]. Two vortical structures have been identified: one located near the flame bulge region on the oxidizer side, which leads to flame flickering, and the other identified as an inner vortex that is due to shear layer instability. These two vortical structures are widely observed in laminar jet flames regardless of fuel type \[3\]. In addition, a unique toroidal vortex at the end of a potential core was observed when the fuel jet velocity was less than that of coflow air in heavy hydrocarbon fuels \[153\]-\[155\].

For the validation of various combustion models, boundary conditions (BCs) in a simulation should be accurately specified. The inlet BC adopted in simulations for axial fuel velocity in a coflow burner usually has either a uniform or parabolic profile. Due to the strong effect of buoyancy on burnt gas, the centerline velocity in a coflow diffusion flame could reach \(O(1 \text{ m/s})\) when the fuel and coflow velocities are \(O(0.01 \text{ m/s})\) and the nozzle diameter is \(O(1 \text{ cm})\) \[155\]. For this reason, it has been suggested that a simple uniform or parabolic inlet velocity profile at the nozzle exit may be enough for predicting the overall flowfield \[147, 154\]. However, a systematic test to confirm the near-nozzle flow-field in small coflow diffusion flames has not yet been conducted, particularly when considering the fuel density effect.

In this regard, we investigated the hydrodynamic structure of small coflow diffusion flames with various gaseous hydrocarbon fuels, taking into consideration the density difference compared with air. A complex recirculation zone structure is reported near the exit of the nozzle for fuels heavier than air. By adopting numerical simulations, the location of the inlet BC for fuel is found to be important for the accurate prediction of the experimentally observed flow-field. More importantly, the calculated temperature field can also be influenced appreciably by the location of the
inlet BC.

3.2 Experiment

A coflow burner was used. The fuel nozzle consisted of a stainless steel tube with an inner diameter \( d \) of 10.8 mm and a thickness of 1.0 mm, a typical nozzle size in studying coflow diffusion flames [147]. The length of the nozzle was 855 mm to allow for the flow to be fully developed in the laminar regime. The coflow air was passed through plastic beads and a ceramic honeycomb so that the flow was reasonably uniform.

The fuels tested were methane, ethylene, propane, and n-butane (> 99.5%). Compressed air was used for the coflow, which was set at 6.2 cm/s. Mass flow controllers were used for the control of the flow rate. The flame heights (defined by the soot luminous zone) for the fuels were maintained near 4.3 cm such that the mean fuel jet velocities \( u_{\text{jet}} \) were 4.45, 2.21, 1.40, and 1.05 cm/s for methane, ethylene, propane, and n-butane, respectively. Once the burner was thermally stabilized after sufficient time from ignition, no flame oscillation was encountered for any of the tested fuels.

An Ar-ion laser (Spectra-Physics, Stabilite2017) at 488 nm with a power of 1.5 W was used with \( TiO_2 \) particle (0.2 \( \mu m \)) seeding to visualize the qualitative flow patterns of the fuel jets. A set of micro-lenses (Leica, Z16APO) was used for magnification with a digital camera. A double-pulse high-speed PIV system (LaVision, 3DFlowMaster) was used for flow-field characterization. Based on an empirical formula for a velocity shift due to gravity acting on seed particles, negligible measurement error could be guaranteed even at such low jet velocities [156].
3.3 Results and Discussion

3.3.1 Flow Characteristics

Photographs of the visible flames (1/500 s exposure time, F6.3) are shown in Fig. 3.1. The visible flame heights are approximately the same and no noticeable differences were found, except in the intensity and distribution of the yellow luminous zones. The variation in the brightness is due to fuel-specific sooting characteristics; methane (ethylene) has less (more) sooting compared with propane and n-butane [157]. These images were captured after twenty minutes of operation, such that the nozzle would be expected to have reached its thermal steady-state. These images were captured after twenty minutes of operation, such that the nozzle would be expected to have reached its thermal steady-state.

![Photographs of flames tested.](image)

Figure 3.1: Photographs of flames tested.

In Fig. 3.2 the near-nozzle flow-field is visualized from the pathlines of the seed particles by the Ar-ion laser with the exposure time of 1/160 s, together with the PIV data (with a time interval of $D_t = 500 \, \mu s$). In all cases, the pathlines are bent towards the centerline, an indication of strong buoyancy and acceleration of the axial
velocity toward the downstream. In the cases of propane and n-butane, pockets of slowly moving particles are observed (concentrated dots) very near the nozzle exit.

Figure 3.2: Flow visualization with Mie scattering of seed particles (a-d) and PIV results (e-h).

The PIV data are represented in color-coded velocity vectors and streamlines. Again, the difference between the methane/ethylene cases and propane/n-butane cases is appreciable. The cases of propane/n-butane exhibit highly deflected streamlines near the nozzle exit. Because a dynamic range of velocity for the main flow
is $O(10^2)$ higher than that for the central region of the near-nozzle, $\delta t$ for PIV was increased to 2.5 ms in analyzing the near-nozzle flow structure. The results in Fig. 3.3 clearly show the existence of a recirculation zone. The n-butane flame exhibited a larger recirculation zone than did the propane flame, which can be attributed to the stronger negative buoyancy force acting on n-butane than on propane. The observation of the recirculation zones very near to the nozzle exit for the fuels heavier than air indicates that they drastically distort the velocity profile at the nozzle exit from the parabolic one. This point will be further discussed in detail later.

![Figure 3.3: Close-up views of the flow-field with PIV near the nozzle exit for propane (a) and n-butane (b).](image)

### 3.3.2 Effect of Nozzle Heating

A nozzle heating effect appreciably influences the velocity profile at the nozzle exit in laminar coflow diffusion flames \[158, 160\]. However, it is a difficult task to accurately measure nozzle wall temperatures such that experiments to describe the quantitative influence of a heated nozzle on the velocity field are rather limited.
To demonstrate the influence of nozzle heating, the flow-fields were visualized with the Ar-ion laser under the three different experimental conditions outlined in Fig. 3.4: (1) cold flow of fuel and air (cold flow/cold nozzle), (2) after externally blowing off the flame (cold flow/heated nozzle) typically within a few seconds, and (3) immediately after ignition (reacting flow/cold nozzle), typically within a few seconds before the nozzle is sufficiently heated by a flame. Note that the reference flames with thermally stabilized nozzles and after twenty minutes of operation (reacting flow/heated nozzle) are shown in Fig. 3.2. The reacting flow/cold nozzle cases should be noted in particular because the heat transfer from the nozzle to the fuel stream can be reasonably neglected in the simulation of such conditions. This point will be discussed further.
Figure 3.4: Flow visualization with Mie scattering of seed particles for various nozzle conditions with and without flames.

For the cold flow/cold nozzle cases, the propane and n-butane fuels rapidly lose their axial momentum due to the buoyancy being directed vertically downwards as a result of the densities of these fuels being greater than air and a stagnation region being formed. In the cases immediately after blowing off a flame (cold flow/heated nozzle), the heated nozzle was found to appreciably influence the flow-fields for the propane and n-butane cases, with large-scale vortices near the nozzle. This phe-
nomenon persisted over several minutes. In the cold flow cases with methane and ethylene fuels, the streamline contractions are more pronounced with the heated nozzle as compared with the cold nozzle cases. For the reacting flows with a cold nozzle, the qualitative flow patterns seem to be similar to those of the reacting flow/heated nozzle cases (Fig. 3.2). Note that in the cases of the cold flow/heated nozzle with the propane and n-butane fuels, the recirculation zones are much larger than in the cases for the reacting flows with flames.

To further explore the detailed flow-fields, axial velocities were measured by the PIV and the results are shown in Fig. 3.5. The radial profile of the axial velocity component at 1 mm above the nozzle exit (Z = 1 mm) (a) and the axial profile of axial velocity along the centerline (r = 0) (b) are compared for the cold (symbols) and heated (lines) nozzle cases of reacting flows with flames. Since the methane flame with the cold nozzle showed instability, with slight fluctuations near the tip of the flame, the experimental range of velocity fluctuation is also represented.
The results (a) show that the radial profiles of the axial velocity are far from the fully developed parabolic one, and these profiles demonstrate an appreciable acceleration especially near the nozzle rim region. This flow acceleration can be mainly attributed to the buoyancy exerted on the burnt gas in a high-temperature flame zone along the mixing layer of the fuel jet, irrespective of the thermal conditions of the fuel.
nozzle. In fuels like propane and n-butane that are heavier than air, due to the formation of the recirculation zone near the nozzle, a negative velocity component exists near the centerline of the nozzle. This can be attributed to the negative buoyancy exerted on the fuels being heavier than air. The effect of nozzle heating on the axial velocity profile at $Z = 1 \text{ mm}$ is relatively small. However, the nozzle heating effect is pronounced for the fuels with a density lighter than (methane) and nearly the same (ethylene) as air. For example, the methane flame shows a dip in the velocity near $r = 0$ with the cold nozzle whereas it displays a reasonably flat velocity profile with the heated nozzle.

The axial velocity profile along the centerline (b) shows appreciable acceleration. This can be attributed to the integrated effect of the buoyancy from burnt gas on the flow structure including air entrainment. Again, not much difference is observed according to the thermal conditions of the nozzle for propane and n-butane fuels, while the methane and ethylene cases exhibit noticeable differences near the nozzle, though these differences diminish toward the downstream. The nozzle material could influence the thermal condition at the nozzle wall. However, based on the above observation, the effect of the nozzle material may have a secondary effect on the formation of the recirculation zone.

These results indicate that the buoyancy effect from fuel density is an important factor in the development of the recirculating flow near the nozzle, while nozzle heating accelerates the axial velocity near the nozzle, particularly for fuels with a density lighter than or similar to air.

### 3.3.3 Numerical Simulations

It has been suggested that since the velocity profile at a nozzle exit is rapidly distorted by the buoyancy effect with a flame \[154\], numerical results may be insensitive to inlet BCs \[147\ 154\]. This may be true when predicting the overall behavior of laminar
coflow diffusion flames with a moderate Reynolds number, such as flame flickers in which a large spatial domain is involved. However, in testing the validity of various combustion models interacting with local flow characteristics in small diffusion flames (e.g., soot formation), based on the present observations, an accurate specification of inlet BCs may be required.

To test this aspect, numerical simulations were conducted for the methane and propane cases, as representative of fuels with densities lighter and heavier than air, respectively. A DNS-based code (Run2D) for axisymmetric reacting flows was used, based on solving time-dependent Navier-Stokes, energy and species equations under the low Mach number approximation \[149\]. A second order central difference scheme based on a staggered grid was adopted for spatial derivatives and a fourth-order six-stage Runge-Kutta method was used for the time integration. Details of the code have been reported previously \[149\]. For computational efficiency, a non-uniform-grid structure was used. The cylindrical coordinate system \((r, z)\) represents the radial and axial coordinates, respectively, with \(Z = 0\) at the nozzle exit.

The axisymmetric computational domain was 3 cm by 18 cm with non-uniform grids of \(64 \times 256\). The computational domain included the inside of the nozzle up to 70 mm in depth. To test the specific locations of inlet BC \((Z_i)\) of the fuel, values of \(Z_i = 0\) and \(-70\) mm were simulated by specifying a fully developed parabolic velocity profile. The BC for the coflow was specified at \(Z = -10\) mm with a uniform velocity profile. The outlet BC at \(Z = 11\) mm was set as a convective BC, and a non-permeable BC was used at the cylindrical wall. Fuel and coflow velocities were set at the same values as those in the experimental conditions. The grid system and radial computational domain have been tested for the case of \(Z_i = 0\) for accuracy.

One-step overall reactions for methane \[161\] and propane \[162\] were adopted. Although detailed chemical structures cannot be captured, as the flame size and heat release are controlled mainly by diffusional processes, the overall flow-field is expected
to be reasonably well predicted. Thermodynamic and transport properties were evaluated by the CHEMKIN III and TRANSPORT Package [163,164], respectively.

Accurate specification of the wall temperature is rather difficult. One reason is that the honeycomb in the coflow air passage will interact thermally with the outer nozzle tube. Instead of a detailed investigation of the nozzle heating effect, the qualitative effect of the nozzle heating has been tested. For the simulation of a heated nozzle with \( Z_i = -70 \) mm, the nozzle temperature was measured with K-type thermocouples and found it to be about 403 K at about 1 cm below the nozzle exit, which is comparable to the previously measured value [165]. The measured temperature was assigned along the tube wall for the heated nozzle cases, while the temperature of the nozzle was set at 298 K for those with the cold nozzle cases. The numerical results with \( Z_i = 0 \) represented the cases with the cold nozzle only.

All the results calculated exhibit a buoyancy driven instability with varying degrees of oscillation near the flame tip region, having a typical oscillation frequency of about 12 Hz, which corresponds to typical frequency by the Kelvin-Helmholtz instability. It has been shown that such oscillation is promoted when the flame temperature is over-predicted without considering radiative heat loss [147]. Here, the computational results presented include the range of oscillation (marked by shading).

A comparison of experimental and simulation results for propane is shown in Fig. 3.6. The simulated radial (a: at \( Z = 1 \) mm) and axial (b: at \( r = 0 \)) profiles of the axial velocity with \( Z_i = 70 \) mm (lines) could predict the corresponding experimental velocity profiles (symbols) satisfactorily for each thermal state of the nozzle. A near inverse-parabolic shape of the radial profile can also be identified at \( Z = 0 \) from the simulation, whereas for the case specifying BCs at \( Z_i = 0 \), the profiles deviate appreciably from the experimental data. In particular, for the axial profiles (b), the predicted recirculation zone with \( Z_i = 0 \) around \( 1.8 < Z < 3.8 \) mm, with a negative axial velocity component, is inconsistent with the experimental data of \( 0 < Z < 2 \).
mm.

It is interesting to compare the calculated temperature profiles for the cold nozzle cases along the center line (c). In the case with $Z_i = 0$, the temperature along the axial coordinate is appreciably underestimated by 160 K, as compared with the case of $Z_i = 70$ mm in the downstream region. This difference is even larger near the nozzle, for example, 197 K at $Z = 1$ mm. However, the temperature difference is 47 K in the downstream when compared with the cold and heated nozzle cases with $Z_i = 70$ mm. This implies that flow modification due to the location of inlet BC has a stronger influence on the overall temperature on the fuel side than does preheating from the heated nozzle. Note that at the nozzle exit for the cold nozzle with $Z_i = 70$ mm, the temperature at the centerline even reaches as high as 425 K due to the existence of a recirculation zone.
Figure 3.6: Simulation results of propane compared with experimental results for various nozzle conditions and the location of the fuel inlet BC: (a) radial profiles of the axial velocity at $Z = 0$ and 1 mm; (b) axial profiles of the axial velocity at $r = 0$; (c) axial profiles of the calculated temperature at $r = 0$.

For the methane flame (Fig.3.7), the calculated results with $Z_i = 70$ mm successfully predict the corresponding experimental results for both the heated and cold
nozzle conditions. Again, the calculation with \(Z_i = 0\) fails to reproduce the experimental data. The importance of the location of the inlet BC in simulating lighter fuels than air is shown in Fig. 3.7. The temperature difference of the cold nozzle between the cases with \(Z_i = 0\) and 70 mm reaches up to 226 K at \(Z = 6\) mm. In the downstream region, such differences are even larger than those between the cold and heated nozzle cases.
Figure 3.7: Simulation results of methane compared with experimental results for various nozzle conditions and the location of the fuel inlet BC: (a) radial profiles of the axial velocity at \( z = 0 \) and 1 mm; (b) axial profiles of the axial velocity at \( r = 0 \); (c) axial profiles of the calculated temperature at \( r = 0 \).

Since soot formation is sensitive to the residence time as well as the local temperature, large discrepancies in the velocity and temperature profiles could lead to...
inaccurate predictions. It is interesting to observe previous computational results with the inlet BCs specified at the nozzle exit. In a previous study, the temperature at the nozzle exit was set at 420 K to predict measured temperature field, and the nozzle heating effect was suggested to be responsible for this correction \cite{158}. Other researchers focused on heat transfer inside the fuel tube to predict experimental results of soot formation \cite{159,160}. The present result suggests that flow development inside the fuel tube and consequent change in the near-nozzle flow field had a strong influence on the temperature field.

Note that the inlet BC is specified at $Z_i = 70$ mm, which is sufficiently far inside the nozzle. To provide reasonable estimation in specifying the location of the inlet BC, $Z_i = 7$ mm was tested based on the profiles in Fig. 3.6. The results are nearly identical with the case of $Z_i = 70$ mm. In this regard, approximately one diameter in depth may be sufficient for accurate simulation under the present test conditions, while the influences of jet velocity and fuel density should be tested in the future.

3.3.4 Effect of the Reynolds Number on the Recirculation Zone

We extended our investigation to higher Reynolds numbers of the fuel stream, focusing particularly on the recirculation zone for n-butane fuel. The Reynolds number, $Re$, based on the nozzle diameter and the kinematic viscosity of n-butane, was increased up to $Re = 359$, which is of particular importance in flame instability studies \cite{3,154}.

Figure 3.8 shows the flow visualization with increasing $Re$. The size of the recirculation zone becomes larger and the radius of the flame near the nozzle enlarges, pushed by the recirculation zone. As $Re$ becomes larger than 73, the recirculation zone shows weak oscillatory behaviour. The structure of the recirculation zone becomes complex. At low $Re$, it has a single vortical structure, while for $Re = 359$, a large-scale vortical structure can be identified from the pathlines in the upper region.
of the recirculation zone. The flow-field with increasing $Re$ shows that more than one vortical structure is formed below the large-scale toroidal vortex.

![Figure 3.8](image)

Figure 3.8: Flow visualization of n-butane flames for $Re = 180$ (a) and 359 (b), and the vortical structure with PIV for $Re = 180$.

To understand this behavior in detail, PIV measurements were conducted and analyzed for $Re = 180$ (Fig. 3.8c). The arrows represent velocity vectors, with pseudo-colors for their magnitudes and streamlines presented by lines. At least two more counter-rotating vortical structures can be identified from the streamline plot below the large-size toroidal vortex in the lower region of the recirculation zone. This observation indicates that complex recirculation structures are formed as $Re$ increases.

The increase in $Re$ from increasing jet velocity influences the relative intensity of buoyancy and convection, through the Froude number, $Fr$, defined as $u_{jet}/(gd)^{1/2}$, where $g$ is the gravitational acceleration. Note that since $Fr$ does not include a fuel density effect, the Richardson number,$Ri = \Delta \rho gd/(\rho_f u_{jet}^2)$, can better describe the formation of the recirculation zone, where $\rho_f$ is the density of the fuel and $\delta \rho$ is the
density difference between fuel and air. Thus, in explaining the vortex formation near the nozzle, the present flame conditions can be categorized as follows: (1) \( Ri < 0 \) (methane and ethylene) and (2) \( Ri > 0 \) (propane and n-butane), which correspond to the positive buoyancy and negative buoyancy exerted on the fuel, respectively. The dependences of the nozzle diameter and jet velocity require further study.

### 3.4 Concluding Remarks

We investigated near-nozzle flow-fields in small laminar coflow diffusion flames with methane, ethylene, propane, and n-butane fuels. For the fuels those are heavier than air (propane and n-butane), recirculation zones were newly identified near the nozzle exit by the negative buoyancy exerted on the fuels. With an increasing Reynolds number, the flow in the recirculation zones exhibit a complex nature, having at least three vortical structures. Quantitative flow-fields were measured by PIV under cold and heated nozzle conditions. The nozzle heating effect was pronounced for the fuels with densities lighter than air, while the effect was small for the fuels with densities heavier than air.

Numerical simulations were conducted by specifying the fuel inlet boundary conditions at several locations. When the BC was specified at a position sufficiently upstream from the nozzle exit, the simulation results predicted the experimental near-nozzle flow-field well, regardless of the thermal state of the nozzle. The parabolic velocity profile changed rapidly to a near U-shape profile near the nozzle by the buoyancy exerted on burnt gas. When the parabolic inlet BC was specified at the nozzle exit, the predicted profile deviated greatly from the experiment. A comparison of these two cases in specifying inlet BCs revealed that the temperature along the centerline could differ about 200 K along the centerline in the downstream region. The present study also emphasized the importance of specifying inlet boundary conditions.
in simulations, particularly in testing various combustion models using small coflow diffusion flames.
Chapter 4

AC Electric Field Induced Vortex in Laminar Coflow Diffusion Flames

4.1 Introduction

The application of sub-critical electric field, corresponding to the field weaker than electrical breakdown field intensity, to modulate combustion characteristics has drawn attention for decades. Abundant charged species generated through chemi-ionization in a reaction zone of a flame can be accelerated by the Lorentz force when an electromagnetic field is applied [89]. This leads to an increase in diffusion flux and potentially reaction rate through increased kinetic energy of associated charged particles. The collision of accelerated charged particles to neutral molecules transfers momentum resulting in a bulk flow of the ionic wind [9, 89, 166, 167]. The combined effects of diffusion and reaction enhancements could affect the flame propagation speed [70], although the respective contributions have yet to be identified.

The ionic wind effect has been most widely studied by applying direct current (DC) [31, 34, 78]. The influence of AC has drawn attention more recently. Drews
et al. [92] reported that a steady modified flow pattern can be generated in a burnt
gas region with high-frequency AC electric fields. In addition, the concept of bi-ionic
wind has been proposed [83], resulting from different dynamic responses from positive
and negative ions coexisting in a flame zone.

Recently, sub-critical AC electric fields have been used widely in flame studies.
Depending on the frequency and voltage of AC, various interesting flame responses
have been observed, e.g., enhancement of flame stabilization characteristics and in-
creased propagation speed of edge flames [70, 74, 80, 83, 84]. High voltage AC also
triggered wrinkling of the flame surface in outwardly propagating flames, similar to
the effect of thermo-diffusive instability for fuels with non-unity Lewis numbers [73].

Compared with DC electric fields, it has been demonstrated that AC electric fields
induce localized forces on flame sheet to create steady ionic winds even with a shielded
electrode, while DC electric field has minimal effect [92]. Note that a time-varying
electric field when applying AC may also induce a magnetic field, according to the
Maxwell equations. Although the Lorenz force due to the induced magnetic field is
expected to be very small as compared with applied electric field, the effect of induced
magnetic field, showing dependence on the magnitude and time-variation of electric
field, may be observed.

In the present study, in order to identify the effect of induced magnetic field when
applying AC, we investigated small coflow diffusion flames by varying the amplitude
and frequency of applied AC. New observations of the formation of vortical structures
near the exit of the fuel nozzle will be reported, together with subsequent changes in
the flow field and characteristics of the soot and PAH zones.
4.2 Experiment

The apparatus consisted of a coflow burner and flow controllers, an AC power supply, a planar laser-induced fluorescence (PLIF) system, a laser-induced incandescence (LII) system, and a particle image velocimetry (PIV) setup. The coflow burner had a central stainless steel tube with an i.d. of 10.8 mm, thickness (d) of 1.0 mm and length of 855 mm in order for the flow inside to be fully developed. The coflow air passed through plastic beads and a ceramic honeycomb so that the flow would have a reasonably uniform velocity profile at the exit, which had an i.d. 150 mm. Apart from the fuel nozzle, all other parts were made of acetal resin to provide electrical insulation.

The fuel used was propane (> 99.5%) and compressed air was used as the oxidizer. Flow rates were regulated by mass flow controllers calibrated with displacement-type dry calibrators. The fuel and air velocities were 1.40 and 6.2 cm/s, respectively, corresponding to typical small laminar diffusion flames without exhibiting instability.

The AC power supply consisted of an amplifier (TREK, 30/20A) and a function generator, which supplied sinusoidal waveform. The applied voltage ($V_a$) and frequency ($f_a$) ranged 0 - 5 kV (rms) and 0 - 8 kHz, respectively, and were monitored with an oscilloscope and a 1000:1 voltage probe. Only the high voltage output of the power supply was connected to the nozzle to apply an electric field to the flame. Thus, the ground electrode for the flames could be treated as a large imaginary sphere surrounding the nozzle. This type of single-electrode configuration has been adopted for studies of flame stabilization characteristics with electric field [70,71,74,82,84,107].

The PLIF setup consisted of a Nd:YAG laser (Continuum, Powerlite DLS), a dye laser (Continuum, ND6000), and a frequency doubler (Continuum, UVT). OH radicals (excited at $Q_1(6)$ line of 282.96 nm [139]) and PAHs (excited at 283.00 nm [168]) were measured using the PLIF setup with an intensified charge-couple device (ICCD) camera (Princeton Instruments, PI-MAX3 1024i) and a set of UG 11 and WG
305 filters. Forty images were accumulated with a correction for background noise. The PLII system for soot volume fraction measurement consisted of a Nd:YAG laser (Spectra-Physics, Quanta-Ray Pro; 40 mJ at 532 nm) and the ICCD camera (detected at 450 nm with 25 nm FWHM filter) to obtain a saturated LII signal.

The PIV setup (LaVision, 2D FlowMaster) with TiO\textsubscript{2} particle (0.2 µm) seeding determined the velocity field. A continuous wave Ar-ion laser (Spectra-Physics, Stabilite 2017) was also used for flow visualization from a Mie scattering with a digital camera and a high-speed (Photron, MC2) camera.

4.3 Results and Discussion

4.3.1 Flame Behavior with AC Electric Field

In Fig.4.1 flame photographs are shown for the baseline case without applying an electric field (a) and the cases with various applied voltage and frequencies (b to e). The yellow luminous region for the baseline case, an indication of the sooting zone by the blackbody radiation from soot particles, is marked as the two dotted lines for comparison. The sooting zones were altered slightly by the electric field, being narrower in width and longer in height. The dark zone between the nozzle and the sooting zone along the axis was extended with the electric field. The soot zone becomes weaker in its luminosity with either increasing voltage or increasing frequency, which will be elaborated further. Other than these changes, no other appreciable differences could be observed.
To further clarify the change in the soot luminosity, PLII images, as representations of the soot volume fraction, are shown in Fig. 4.2 for various $V_a$ at $f_a = 250$ Hz. The PLII signal intensity weakens and the area of soot zone reduces appreciably in the downstream as the voltage becomes high. As $V_a$ increases, say over 3 kV, the near nozzle region starts to exhibit LII signals, although it cannot be identified with the naked eye. The existence of LII signals near the nozzle exit implies that there are appreciable changes in either flow or temperature fields as a result of applying the electric fields.
To further understand the variation in the flame structure, superimposed images of OH PLIF (in linear scale), indicative of the main reaction zone, and PAH PLIF (in log scale), being soot precursors, are shown in Fig. 4.3 for various $V_a$ at $f_a = 250$ Hz. These PLIF images were normalized by the maximum signal intensity at $V_a = 4.5$ kV, and two different values of a noise filter were used for Fig. 4.3a,b and c-e to clearly show the major regions of PAHs. The PAH zone is shifted appreciably towards the nozzle exit and the maximum intensity becomes over 30 times stronger than that in the baseline case with increasing voltage. This result supports the observation that soot particles are formed near the nozzle exit (Fig. 4.2c-e). Although not shown, similar behavior can be observed with increasing frequency at a fixed voltage.
In a typical diffusion flame, PAHs and subsequently soot are formed through fuel pyrolysis before reaching a main reaction zone. The PAH region typically has a temperature range of 1000 - 1500 K \cite{168, 169}. A blue flame zone exists near the nozzle exit and a PAH zone appears beyond a certain distance from the nozzle exit, as shown in 4.3a. While for \( V_a \geq 3\, kV \), the PAH zones appear to exist even inside the nozzle region, and the main PAH zone is appreciably separated from the downstream soot zone. The OH zone from the PLIF image shows only a minor change as the flame length elongates slightly with the voltage. The maximum OH intensity is only minimally influenced by the electric field.

To obtain quantitative variations in PAHs and soot volume fraction with AC voltage, the volume integrated signals from the PAH PLIF and LII measurements are shown in Fig.4.4 which were normalized with the condition at 4.5 kV and the baseline cases, respectively. Three distinct regimes can be identified: (I) low voltage regime of \( 0 < V_a < 2.6\, kV \), characterized by the slow increase in the PAHs and by the
slow decrease in the soot volume fraction; (II) transition regime of $2.6 < V_a < 3.4$ kV characterized by a rapid increase in PAHs up to 25 times and a decrease in soot volume fraction of about 30 percent; and (III) a high voltage regime of $V_a > 3.4$ kV characterized again by slow changes in PAHs and soot. Note that the transition regime can also be characterized by the sudden shift of the PAH zone toward the nozzle exit and the formation of an annular soot zone near the nozzle exit, as shown in 4.2.

Figure 4.4: Variations of volume integrated PLII of soot and PLIF of PAHs with applied voltage at $f_a = 250$ Hz.

4.3.2 Formation of Vortex Ring

PAHs grow from incipient rings such as benzene, which are formed from pyrolysis in a reasonably high temperature [21]. Thus, the existence of the high concentration of
PAHs near the nozzle exit suggests that the temperature in this region is relatively high. To elucidate the phenomenon, flow fields were visualized from the Mie scattering by seeding $TiO_2$ particles (0.2 $\mu$m) to the fuel stream for the baseline case and the flame with $V_a = 4$ kV and $f_a = 250$ Hz. The Mie scattering images near the nozzle exit taken with the PIV laser and a laser line filter centered at 532 nm are shown in Figure 4.5. The corresponding OH images are superimposed with pseudo-color and the PAH LIF signals are shown as iso-intensity contours on the left sides of the images.

For the baseline case (a), the region of seed particles coming out of the nozzle rapidly contracts toward the downstream. This is a behavior typical in coflow diffusion.
flames as a result of the buoyancy effect acting on burned gas. The Mie scattering from soot particles can also be observed. Note that individual seed particles can be identified by the 8 ns duration Nd:YAG laser, while for the soot zone which has finer particles, no individual soot particles can be identified.

With the electric field (b), the near-nozzle soot zone as observed from the LII signal in Fig. 4.2 can be identified. PAHs also exist in this region shown as the iso-intensity contours (see also Fig. 4.3d). The ring type structure of the soot particles in this region suggests a vortical structure. The recirculating nature of the flow can be further substantiated by the contraction of the seed particle region at the nozzle exit in the fuel stream toward the center of the jet.

The PIV data for flow fields are compared in Fig. 4.6. For the baseline case (a), the acceleration of axial velocity by a strong buoyancy effect can be clearly seen at say above 1 cm downstream from the nozzle, reaching an axial velocity of about 1 m/s. With the electric field (b), a contraction of the fuel flow region can be identified, leading to an appreciable acceleration of the fuel flow near the central region of the nozzle exit. The maximum velocity near the nozzle exit reaches about 40 cm/s. The flow velocity inside the recirculation zone cannot be identified because the seed particles cannot penetrate into it.
Figure 4.6: PIV result with seed particles; (a) baseline flame and (b) flame with \( V_a = 4 \) kV and \( f_a = 250 \) Hz.

To further elucidate the recirculating vortex region, a planar Ar-ion laser beam with a thickness of 2 mm illuminated horizontally the near nozzle region for the flame with \( V_a = 4 \) kV and \( f_a = 250 \) Hz. The image without seed particles is shown in Fig. 4.7a, in which the toroidal vortex from the scattering of fine-sized soot particles can be clearly identified.
The rotational direction of the vortex, shown on the right side of the image in Fig. 4.5b with the short-pulse Nd:YAG laser is expected to be clockwise to be consistent with the accelerated fuel flow field in the central axis region. Given that the ambient air is entrained by the buoyancy, a counter-rotating recirculation zone should exist outside the recirculation zone. In Fig. 4.7, a stagnation point can be identified from the pathlines by the seed particles and large size soot particles within the vortex ring region taken with 1/160 s exposure time. It suggests the presence of a counter-rotating vortex outside the observed toroidal vortex. This point will be discussed further.

Due to the existence of a recirculation zone, heat generated from the hot flame zone is transferred into the vortical structure. The increased temperature and prolonged residence time within the vortex provide a favorable environment for PAHs and soot to grow, as indicated by the overlapped image in Fig. 4.5b for OH, PAHs and soot particles in this zone.

As mentioned, the fuel velocity at the center of nozzle exit with $V_a = 4$ kV and $f_a = 250$ Hz was about 40 cm/s, nearly 30 times higher than the average velocity of the baseline case. Thus, the convection time along the centerline from the exit to
around 2 cm above the nozzle decreases appreciably from that for the baseline flame. Although the increased residence time inside the recirculating vortex promotes PAHs and soot formation near the nozzle rim region, the decrease in the residence time along the axis could decrease the soot volume fraction in the downstream sooting zone with the electric field, as can be observed in Fig. 4.2.

4.3.3 Mechanism for the Formation of Recirculation Zone

To further understand the mechanism of the formation of the toroidal vortex near the nozzle with AC, the onset conditions were investigated in terms of applied voltage and frequency. The formation of the toroidal vortex is associated with the locally enhanced PAH PLIF signal and Mie scattering signal from soot particles near the nozzle (Figs. 4.2 and 4.3). Thus, we used a Mie scattering signal near the nozzle rim in determining the onset conditions using the UV laser (283 nm). When the AC frequency was varied for a specified voltage, the scattering signal near the nozzle increased abruptly within 1 percent of a margin of error in the AC frequency. This sudden change in the flow pattern in forming the vortex near the nozzle can be conceived as a bifurcation phenomenon similar to various hydrodynamic instabilities such as the Bénard convection and Kelvin-Helmholtz instability. In Fig. 4.8 it can be seen that the onset frequency to generate the toroidal vortex decreases as the voltage increases.
We also conducted experiments by applying both positive and negative DC to the nozzle to test a time-invariant electric field. Up to $\pm 10$ kV of DC, no noticeable change was observed. This suggests the importance of the time-varying electric field to the formation of the recirculation zone. Inspired by this, a viable mechanism of the vortex formation, which is triggered by AC fields, is hypothesized as follows.

With an AC electric field, a magnetic field can be induced due to the displacement current by the time-varying component of the electric field [170]. Charged particles such as ions in a flame zone produced by chemi-ionization, together with PAHs and soot particles [1, 171, 172], are subjected to the Lorentz force, \( \mathbf{F} = q[\mathbf{E} + (\mathbf{v} \times \mathbf{B})] \), where \( \mathbf{E} \) and \( \mathbf{B} \) are the electric and magnetic fields, respectively, \( q \) is the charge of the particle, and \( \mathbf{v} \) is the velocity of the charged particle. The velocity component consists of convectional velocity and ion drift velocity, which is defined as \( \mu \mathbf{E} \) [89], where \( \mu \) is the ion mobility. A first estimation of the maximum electric field intensity \( E_{\text{max}} \) is

![Graph showing critical onset conditions for inner recirculation in terms of applied voltage and frequency.](image)

Figure 4.8: Critical onset conditions for inner recirculation in terms of applied voltage and frequency.
the applied voltage divided by a radius of curvature of electrode, which can be the nozzle thickness. Thus, $E_{max} \sim O(1kV)/O(1mm) \sim O(10^6V/m)$. An electric field calculated using the Maxwell 2D software also confirmed that electric field intensities near the nozzle were $\sim O(10^6V/m)$ with $V_a = 4 \text{kV}$. By taking a typical ion mobility of $O(10^{-4}m^2/V \cdot s)$, the ion drift velocity can reach up to $O(10^2m/s)$ near the nozzle, which is much larger than the convectional velocity shown in Fig. 4.6.

A schematic of $E$ and induced $B$ when applying AC is presented in Fig. 4.9 in the green and red colors, respectively. The direction of the curvilinear motion of positively charged particles is also marked as the blue arrows. This is because positive ions, such as $HCO^+$ and $H_3O^+$, are abundant compared with negative ions in a reaction zone, which can be understood based on electrical neutrality between positive ions and the group of negative ions and electrons. The mass of an electron is too small to contribute to the bulk flow motion of ionic wind. It has also been reported that PAHs and soot are frequently positively charged.

![Figure 4.9: Schematic of electric field ($E$, green lines), induced magnetic field ($B$, red) and resulting curvilinear motion of positively charged particle (blue arrows).](image)

To understand the formation of the toroidal vortex, we have estimated the AC field-induced magnetic force. The magnitude of magnetic force is $F_{mag} = qvB$, where $v$ and $B$ are the magnitudes of the charged particle velocity and the magnetic field,
respectively. Here, we have considered only the ion drift velocity as a main component of the velocity, based on the order of magnitude estimation above. Then, \(v\) can be scaled with \(E\) and it is proportional to the applied voltage as \(v \sim E \sim V \sim V_a\), where \(V = \sqrt{2}V_a\sin(2\pi f_at)\). The Amperes Law suggests that the magnitude of induced magnetic field is expressed with the displacement current \(I_d\) as \(\oint B \cdot dl = 2\pi r_o B = \mu_o I_d\), where \(r_o\) is the radius of the nozzle and \(\mu_o\) is the magnetic constant. Here, the displacement current can be expressed as \(I_d \approx \varepsilon_0(\partial E/\partial t)(2\pi r_0d)\), where \(\varepsilon_0\) is the electric constant. Therefore, \(B \approx \varepsilon_0\mu_o(\partial E/\partial t)d\), where \(\varepsilon_0\mu_o = 1/c^2\) and \(c\) is the speed of light. Since the time derivative of \(E\) can be deduced as \(\partial E/\partial t = 2\pi f_a E\), the magnetic field can be estimated as \(B \approx 2\pi f_a E d/c^2\). Consequently, the AC field induced magnetic force acting on a charged particle can be scaled as \(F_{mag} \sim vB \sim (V_a)(V_a f_a) \sim f_a V_a^2\).

Note that by adopting \(f_a \sim O(10^2Hz), d = 1mm\), and \(v \sim O(10^2m/s)\), a relative ratio of the magnetic force to a corresponding electric field will be \(vB/E \sim O(10^{-15})\). Indeed, the magnetic force is much smaller than corresponding electric field. However, only a small disturbance is required in triggering a hydrodynamic instability.

One of convincing evidences in identifying the mechanism of formation of the recirculation zone is testing the critical onset condition of the bifurcation phenomenon. Noting that \(f_a \sim V_a^{-2}\) in the above, the onset conditions of the formation of the recirculation zone shown in Fig. 4.8 are fitted in the form of \(f_a \sim V_a^{-2}\) and marked with the solid line. The best fit has a proportional constant of \(2.07 \times 10^9[Hz \cdot V^2]\) with \(R = 0.994\), which is required to trigger the formation of recirculating flows. This excellent correlation supports the proposition that a magnetic field induced by the displacement current with AC can be a viable mechanism in generating the toroidal vortex.

As the polarity changes in AC, the direction of rotation should alternate as exhibited in Fig. 4.9 such that the magnetic force has no preferred direction of rotation.
However, a typical flow pattern of a laminar diffusion flame under the influence of fuel flow, buoyancy and subsequent air entrainment near the nozzle region could provide the preferred direction of circulating flow. To further elucidate the underlying physical mechanism, a high-speed movie with the horizontal beam configuration of the Ar-ion laser was taken with 2000 fps for the case of $V_a = 4 \text{ kV}$ and $f_a = 103 \text{ Hz}$. The result clearly shows the pulsating nature of the rotating particles, exhibiting repetitive acceleration and deceleration. We confirmed that such motion was synchronized with the AC frequency. This indicates that the electromagnetic force combined with the favorable direction of flow field generate the rotational motion near the nozzle.

### 4.3.4 Existence of Counter-rotating Vortical Structure

As previously discussed and shown in Fig. 4.7b, a pair of counter-rotating recirculation zones should exist based on the overall feature of flow field. When the AC frequency was further increased to about $f_a = 8 \text{ kHz}$ at $V_a = 4 \text{ kV}$, a counter-rotating outside vortex can be observed, as shown in Fig. 4.10. A bright yellow luminous soot zone appears near the nozzle rim (a) which can be visible even with the naked eye. The visualizations using the Mie scattering with the horizontally aligned Ar-ion laser sheet (b) and the pulsed Nd:YAG laser (c), where the OH and PAH fluorescence are superimposed, clearly demonstrate a pair of counter-rotating vortical structures. The close-up photo (d), with the exposure time of 1/80 s, exhibits the pathlines of large soot particles near the nozzle rim. The trajectories are nearly circular in shape and the traversing angle during the exposure time is relatively insensitive to the radius from the center of the outer vortex (2000 rpm), indicating a nature similar to a forced vortex. The instantaneous cross-sectional image of the outer vortex (illuminated with a single pulse of the Nd:YAG) near the right-side of the nozzle rim (e) indicates that the swirling spiral motion is counter-clockwise. Large soot particles escape from the outer vortical structure, which can be also seen (f). In Fig. 4.10f, the
streamlines for the pair of vortices are also schematically depicted, which is based on
the long-exposure trajectories of large soot particles with the Ar-ion laser. However,
the formation and detailed characteristics of outer visible toroidal vortex should be a
future study.

Figure 4.10: Images of flame with visible outer vortex of soot particles for $V_a = 4$
kV and $f_a = 8$ kHz; flame photo with vortex ring of soot particles nearly nozzle
(a), horizontal Mie scattering image of soot particles exhibiting pair of vortices (b),
superimposed image of Mie scattering with OH and PAH PLIF images (c), close-up
view of outer vortex of soot showing circular trajectory of particles (d), close-up of
cross-sectional image of outer vortex showing counter-clockwise spiral rotation (e),
and schematic of flow pattern (f).

4.4 Concluding Remarks

A new observation of electromagnetically induced toroidal vortex pair near a nozzle
exit was reported for a laminar coflow diffusions flame by applying AC electric fields
to a fuel nozzle. With increasing frequency (voltage) at fixed voltage (frequency),
a drastic change in the location of the PAH zone near the nozzle exit was observed
by the formation of a toroidal vortex. Based on the scaling analysis, the magnitude
of induced magnetic forces due to displacement currents with AC electric fields was
found to be proportional to \( f_a V_a^2 \). The onset conditions for the formation of an inner toroidal vortex for various applied voltage and frequency showed a near constant value of \( f_a V_a^2 = 2.07 \times 10^9 [Hz \cdot V^2] \). Therefore, it can be hypothesized that such a critical value of induced magnetic force could trigger the formation of toroidal vortices, which can be assisted by the ionic velocity due to the electric fields and intrinsic flow configuration of the laminar coflow diffusion flame.

Based on the observations and reasoning, the phenomenon can be explained as follows: (1) charged particles are influenced by electromagnetic fields and form the vortices near the nozzle; (2) heat is accumulated in the vortices by heat transfer from the flame zone increasing the temperature of the vortices; (3) the increased temperature as well as residence time could promote PAH and soot formation in the vortices; (4) along the central region of the jet axis the decreased residence time through the accelerated velocity due to the toroidal vortex resulted in reduction of the soot volume fraction in the downstream sooting zone. Further detailed study is required to better understand the physicochemical mechanisms underlying the formation of the vortices and subsequent PAH and soot formation in this zone.
Chapter 5

Instabilities and Electrical Responses of Small Laminar Coflow Diffusion Flames under AC Electric Fields

5.1 Introduction

Combustion instabilities have been widely observed in practical combustors including gas turbines, industrial furnaces and propulsion engine [174-176]. Such oscillatory phenomena could result in fluctuations in heat release rates, which mainly can either enhance the heat transfer process via increasing soot generation [125,177,178] in nonpremixed flames or lead to resonant oscillations when coupled with pressure oscillations in premixed flames [176,179,180].

In this regard, ability to modulate combustion instabilities could be a desirable feature integrated in modern combustor design. Introducing external forcing as perturbations has been tested to be effective in modulating combustion instabilities. Typical actuators to generate perturbations include, acoustic drivers providing pres-
sure waves \cite{181,183}, servo valves adjusting flow rates \cite{184} and microjets modifying hydrodynamic momentum distributions \cite{185}. These controlling devices have shared a common challenge, the time delay between the actions and associated flame responses. The non-negligible time delay complicates the design of feedback active control system over combustion instabilities \cite{186}.

Flames are under weakly ionized plasma states, since charged particles (mainly \(CH_3^+, H_3O^+, HCO^+, C_3H_3^+,\) and electrons) are generated in reaction zones through chemi-ionization and subsequent ion chemistry \cite{1,2}. Under external electric field, the collision of accelerated charged particles to neutral molecules transfers momentum resulting in a bulk flow of the ionic wind \cite{9}. Acceleration of charged particles could result in enhanced diffusion and gained kinetic energy could influence reaction rates associated with charged particles. A response of ionic wind to external electric field is in milisecond time scale \cite{86,102,186}. When electric field is applied, the resulting perturbations are typically localized near a reaction zone \cite{92} such that electrical power consumption is typically very small \cite{74}.

Studies on electric field effect in modulating flames has received increasing attention. This implies that electric field may be utilized as a viable actuator in controlling a flame. For this, various flame responses to electric field need to be understood first. Marcum et al. \cite{10} reported that DC electric pressure decreased the effective Lewis number below unity and observed thermo-diffusive instabilities. Ryu et al. \cite{107} studied oscillating instability behaviors of laminar nonpremixed lifted flame under low frequency AC electric field and identified several response modes. Kim et al. \cite{83} observed nonlinear oscillating modes of bunsen flames under AC electric field and identified the bi-ionic wind effects, arising from both positive and negative ions. Volkov et al. \cite{103} explored an acoustic transfer function of flat premixed flames under DC electric field and tested a potential in the control of thermo-acoustic instability. Such investigations are still limited for coflow nonpremixed jet flames under
AC electric fields. Also, studies on the response on ion current when applying AC electric fields are still limited.

Recently, AC electric field was found to trigger the formation of toroidal vortices in near nozzle region of small coflow diffusion flames \[187\]. This study is a continuation of the work, focused on the dynamic responses of a small coflow diffusion flame triggered by AC electric field. Various instability modes will be reported along with detailed measurement of ion current responses to AC electric fields.

### 5.2 Experiment

The apparatus consisted of a coflow burner and flow controllers, an AC power supply unit, an electric power measurement setup, and visualization systems. The coflow burner had a central fuel nozzle with 10.8 mm in inner diameter, 1.0 mm in thickness and its length was 855 mm for the flow inside to be fully developed. The coflow air passed through plastic beads and a ceramic honeycomb for the velocity profile to be nearly uniform at the exit of the coflow with 150 mm in diameter. The fuel nozzle was protruded 9.6 mm above the honeycomb. All the parts were made of acetal resin for electrical insulation except for the nozzle to apply electric field.

The fuel used was propane (>99.5%) and compressed air was used as the oxidizer. Mass flow controllers were calibrated with positive displacement type calibrators. The fuel and air velocities were fixed at 1.40 and 6.2 cm/s, respectively, corresponding to a typical small laminar diffusion flames without exhibiting flickering instability when electric field was not applied.

The AC power supplier unit consisted of an amplifier (TREK, 30/20A) and a function generator (NF, WF1973), which supplied sinusoidal waveform. The applied voltage \(V_{ac}\) and frequency \(f_{ac}\) were 0-5 kV (rms) and 0-5 kHz, respectively, which is under reliable working conditions of the power amplifier. The high voltage output
was connected to the fuel nozzle. A stainless steel mesh with a diameter of 150 mm was positioned at 27 cm above the nozzle tip serving as the ground electrode.

The electric power measurement setup consisted of a 1000:1 voltage probe (Tektronics, P6015A), a current amplifier (Stanford Research System, SR570), and a high bandwidth oscilloscope (Tektronics, TPS 2014B). The high voltage probe was attached to the bottom part of the nozzle to measure applied voltage and electric current was measured at the ground side with the current amplifier. A common ground is shared by all equipment to assure a same ground potential. All electric signals were displayed on the oscilloscope and processed in a PC using MATLAB to determine instantaneous power. In all test cases, electric field was applied after 10 minutes operation of the baseline flame without applying electric field such that the burner system could reach in thermally in equilibrium state. In each new test, the jet nozzle was carefully cleaned to exclude any soot deposition on the nozzle electrode.

The visualization systems consisted of a continuous wave Ar-ion laser (Spectra-Physics, Stabilite 2017), a high-speed camera (Photron, SA4), a digital camera and micro-lenses. Local flow structure and dynamic response of flames could be captured with sufficient temporal resolution.

5.3 Results and Discussion

5.3.1 Toroidal vortex formation

The formation of vortical structures in the near-nozzle region of a coflow diffusion flame have been reported previously [187] when applying AC electric field to a stationary coflow flame through flow visualization by Mie scattering from soot particles. An inner toroidal vortex (ITV) ring, having the ring diameter smaller than the nozzle diameter, was observed when increasing voltage and frequency. Figure 5.1 shows the photos of flames along with the Mie scattering images near the flame base using the
planar Ar-ion laser sheet beam oriented horizontally with 1.4 cm in width and 1 mm in thickness (a,b) and oriented vertically with 1.6 cm in height and 1 mm in thickness (c,d) for $V_{ac} = 3$ kV (a,c) and 4 kV (b,d).

Figure 5.1: Mie scattering signals from ITV across critical onset frequencies.

The baseline flame is the case without applying electric field. For a fixed $V_{ac} = 3$ kV (a) with increasing the frequency, no noticeable difference can be observed up to $f_{ac} = 172$ Hz. With a small frequency increment of only 1 Hz to 173 Hz for 3 kV,
the formation of ITV can be clearly distinguished from the Mie scattering signals. For $V_{ac} = 4$ kV (b), a clear distinction of the formation of ITV can be observed by changing $f_{ac}$ from 81 to 82 Hz. This indicates a sharp transition behavior in forming ITV with AC frequency. The vertical images (c and d) confirms recirculating flow structures. Details of flow structure has been reported previously [187].

The existence of ITV near the nozzle rim necessitates an existence of a vortex pair counter-rotating to conform the flow fields of fuel jet and out entrainment air, both having axial upward direction. Such an outer toroidal vortex (OTV) ring, located outside of the inner vortex ring can be visualized even with the naked eyes at much increased $V_{ac}$ and $f_{ac}$. This is shown in Fig. 5.2a for $V_{ac} = 2.5$ kV and $f_{ac} = 5000$ Hz, exhibiting a yellow luminous ring near the nozzle. Such formation of vortex pair structure was conjectured due to electromagnetic perturbations induced by AC electric fields [187].

Figure 5.2: Left a: dual ring structure at 2.5 kV, 5000 Hz, 15 minutes. Right b: nozzle cleaning state at 4 kV, 100 Hz, 30 minutes.
As the vortices are formed, an appreciable amount of soot is deposited on the high voltage fuel nozzle. This can be attributed to the fact that soot particles are formed very near the nozzle, circulating flow and long residence time inside the rings, and potentially due to charges carried by soot particles [17] and their interaction with electric fields. In Fig. 5.2b, the state of high voltage nozzle is demonstrated before applying AC electric field for $V_{ac} = 4 \text{kV}$ and $f_{ac} = 100 \text{ Hz}$ and after 30 min in applying electric field. The result shows that appreciable amount of soot is deposited on the nozzle rim.

Regimes for the formations of ITV and OTV are shown in Fig. 5.3 in terms of $\log V_{ac}$ versus $\log f_{ac}$. The onset conditions for the formation of ITV are marked in red circles, which are determined from scattering signals when an ITV is formed. A fitting curve, based on $V_{ac}$ ranging from 2.5 kV, reveals a near linear behavior in the log-log plot. The reason for the condition of ITV formation at lower voltage, such as 1.5 kV, to be excluded from the fitting will be elaborated later. The formation conditions for OTV are plotted in black lines. The OTV regime depended on the elapsed time from the moment of applying electric field to the baseline flame. As the elapsed time increases from 10 to say 600 s, the regime enlarges, which means that longer time elapsed from the application of electric field, lower frequency and voltage conditions could trigger OTV. This can be attributed to soot depositions on the nozzle rim as shown in Fig. 5.2b, which affects the near nozzle distribution of electric fields and flow. On the contrary, the condition of ITV formation is independent of elapsed time after applying AC electric fields, since soot particles are located about 5 mm downstream of the fuel nozzle for the baseline flame and thus no noticeable deposit onto the nozzle was observed.
5.3.2 Transient flame responses near ITV onset condition

During the formation of ITV, the flow field near the nozzle exit can be distorted significantly and such flow perturbation may further propagate downstream and alter the flame shape. In Fig. 5.4, the transient flame behaviors by changing AC frequency from \( f_{ac} = 50 \text{ Hz} \) (just before ITV formation) to 51 Hz (just after ITV formation) for \( V_{ac} = 5 \text{ kV} \) are recorded via high speed camera at 250 fps. After the change of the frequency to 51 Hz, the flame is elongated suddenly and then stabilizes slowly to a new equilibrium position very similar to that with \( f_{ac} = 50 \text{ Hz} \).
The required $V_{ac}$ and $f_{ac}$ to trigger the sudden perturbations in flame heights coincide with ones obtained via Mie scattering signals from ITV for $V_{ac}$ between 2 kV to 5 kV. This coincidence is obvious since the transient flame height variation is attributed to the sudden fuel velocity perturbation induced by ITV formation. However, for lower $V_{ac}$, such as 1.75 kV, increase in $f_{ac}$ does not drastically trigger such flame transient motions as shown in Fig. 5.5 indicating ITV formation (also the flow field alternation) process becomes rather smooth, distinguishing ITV formation for $V_{ac} < 2$ kV from $V_{ac} \geq 2$ kV cases. This is also the reason that in Fig. 5.3, the fitting curve of ITV formation was only based on $V_{ac} \geq 2$ kV and a deviation of $f_{ac}$ at ITV formation from the fitting curve is shown for $V_{ac} < 2$ kV.

To further understand the transition behaviors shown in Fig. 5.4, the flame height
is recorded across the onset $f_{ac}$ with 1 Hz increment at several $V_{ac}$. Figure 5.6 shows the flame height variation before and after the change in the frequency (marked with the vertical red line) of 1 Hz across the onset condition, where the frequencies after the onset condition is marked. Before the onset of ITV, the flame height is maintained a reasonably constant value (near stationary) for low voltage cases with relatively high frequency ($V_{ac} \geq 4$ kV) with relatively low frequency before the onset frequency.

Figure 5.6: high speed imaging on transient tip behaviors across the onset condition.

Diminishing the amplitude of such flame oscillations at high frequency cases for the low voltages can be explained based on the frequency response of flames on ionic wind effect. For the ionic wind to be developed, a collision response time is required. Since the concentration of ions in a reaction zone is much smaller than that of neutral molecules, multiple collisions are required between accelerated ions by electric field through the Lorentz force and neutral molecules for the ionic wind to be developed [83,102]. It has been shown that for the AC frequency larger than 60 Hz, the ionic wind can not be fully developed. Thus, as the applied voltage decreases, the onset frequency increases such that the flame becomes almost stationary before
the formation of ITV.

The combined effects from both the flow perturbation induced by ITV formation along with the ionic wind are responsible for the flame responses with the change in the AC frequency across the onset condition. The responses in Fig. 5.6 show that in general, the transient fluctuation in the flame height becomes larger as $V_{ac}$ increases. For $V_{ac} = 2.5$ kV and below, even after ITV formation, the flame height fluctuates at low frequency of about 1 Hz. Scattering signals from ITV in these cases show that ITV appears and vanishes periodically.

Electrical signals are measured during quasi-steady state (allowing small amplitude oscillation at $f_{ac}$ due to ionic wind as mentioned) before and after the ITV formation as shown in Fig. 5.7 for $V_{ac} = 5$ kV in terms of the currents $I_{ac}$ and $V_{ac}$ with time. Due to appreciable flow alternations induced by the ITV formation and subsequent changes in the soot volume fraction and PAH concentrations [187], the current might also be altered accordingly, since it is usually accepted that a strong correlation exists between the current and flame properties at least under DC conditions [186]. However, comparing the either the shape or magnitude of $I_{ac}$ before and after the ITV formation, only a small change can be identified. This is reasonable based on the observation of comparable flame lengths before and after the formation of ITV (Fig. 5.4).
Figure 5.7: Power consumption variation with respect to AC frequency.

The averaged power consumption, $\overline{P}$, is adopted by integrating the instantaneous power consumption, defined as $P(t) = V(t)I(t)$, over 1 s using the trapezoidal rule. Note that $\overline{P}$ also includes the contribution from the power consumption of the electrical circuit without flame [92]. The relations of $\overline{P}$ at several $V_{ac}$ and $f_{ac}$ are shown in Fig. 5.8. Note that $\overline{P}$ is in the order of 1-10 mW. This can be compared with the heat generation in the order of 0.1 kW [187]. This at least $10^4$ order of difference between the heat generation and electrical power emphasizes the advantage of utilizing electric field as a viable actuator in modulating a flame.
Figure 5.8: Power consumption variation with respect to AC frequency.

The result shows that the power increases with the frequency and a sudden decrease in $\bar{P}$ across the onset of ITV is observed, with the inset for details for 5 KV. For lower voltage cases, such change in $\bar{P}$ across the formation of ITV occurs in much wider frequency range, consistent with the observations in Fig. 5.5. Comparing the direct photos before and after the ITV formation in Fig. 5.5 and Fig. 5.6, since the flame height remains similar before and after the onset of ITV, the decreased $\bar{P}$ may be partly attributed to the flow field alteration and the reduced flame yellow luminosity.

5.3.3 Flame instabilities after ITV formation

After the onset of ITV at high voltage and frequency of AC, various instability modes occur, including flickering flame, partial pinch-off, and spinning flame. These are
described below.

**Flickering flame mode**

Without applying electric field, a small nonpremixed jet flame could experience a buoyancy-driven instability through the baroclinic torque and the modified Kelvin-Helmholtz instability, typically observed in a flickering mode such as candle flames or dancing flares of pool flames. For very small Froude $Fr$ number, this flickering instability may not be observed since vorticity expansion and stretch effects suppress vorticity generation along a flame such that resulting net vorticity creation downstream is not sufficient to sustain a vortical structure near flame bulge \cite{121}. For the baseline flame used here, without applying electric field, flame flickering instabilities are suppressed, even up to four times of the fuel jet Froude number (or jet velocity). However, once AC electric field is applied, flickering instabilities are observed with different strength depending on applied $V_{ac}$ and $f_{ac}$.
In Figure 5.9 direct photos of flame oscillation mode for $V_{ac}=1.5$ kV and $f_{ac} = 1500$ Hz (a) and flame pinch-off mode for 2.5 kV and 1500 Hz (b). These images were taken after applying AC electric fields for 300 s with the time interval between the images of $\Delta t = 0.008$ s. For the pinch-off case, a tip separation occurs thus two flame heights can be defined as high tip and low tip.

The oscillation frequencies of these two modes are about 12 Hz. This $O(10 \text{ Hz})$ oscillation is consistent with a typical natural oscillation frequency when without applying electric field for the similar nozzle configuration (about 1 cm in diameter)
at higher fuel jet velocity \[3^{188}\]. The result implies that electric field could trigger instability, which eventually develops to a buoyancy-driven instability. To elucidate the flow structure during oscillation, magnified images near the flame base for the pinch-off mode as Fig. 5.9b are shown in c, which were taken with the illumination of Ar-ion laser with 1 mm in thickness and 16 mm in width. The formation of ITV (indicated by the blue recirculation zone) is coupled with the increase in the flame length by the acceleration of the flow in the central region of the jet. As the flame is pinching-off, the flame length decreases. Simultaneously, the size of the recirculating ITV decreases, resulting in the reduction of the flow velocity in the central region. A periodic shedding of the out soot layer in the ITV is also observed (bright blue streaks near flame surface). Although not shown, scattering images for the flickering mode has similar behavior with a weaker strength.

The reason why flickering instability could be triggered under AC might be possibly attributed to the ITV induced modifications over the flow structures, which has proved to be capable to modulate the vorticity generation responsible for the flickering motions \[121\]. Experimentally, it has also been found modified flow fields either by nozzle heating (as shown in Chapter 3) or by artificial created velocity streams \[189\] could modify the flickering instability. Details on the mechanism of AC on inducing the flickers will be future study.

**Spinning flame mode**

Spinning flames were observed in premixed flames \[190\] - \[193\]. For example, Kwon et al. \[192\] reported a nearly planar spinning flames in a sudden expansion tube for methane/air and propane/air flames. Importance of heat loss, preferential diffusion and also hydrodynamic effect were emphasized in inducing flame spinning motions. Spinning flames were also observed in nonpremixed flame in von Krman swirling flows by rotating solid polymethylmethacrylate disk in air \[194\].
A spinning flame mode is observed in nonpremixed jet flames when applying AC electric field with further increased $V_{ac}$ and $f_{ac}$ from the flickering mode AC conditions, near the region of the formation of OTV. One period of spinning flame behavior is shown in Fig. 5.10 for $V_{ac} = 4$ kV and $f_{ac} = 3000$ Hz after applying electric fields for 300s. Direct photos (a) show that the flame is spinning by having near constant flame height. The yellow luminous zone is skewed and the yellow luminous pointing edge is spinning along the nozzle rim as schematically shown in (b). Close up of direct photos along with the Mie scattering by the Ar-ion laser sheet (c) shows clearly the OTV structure (near horizontal yellow ring above the nozzle exit) along with the variation in ITV (green scattering image) during the flame spinning motions. Downstream yellow luminous zone, indicating the sooting region, is asymmetric during the rotation. One edge of the sooting region is contacted with OTV and exhibits azimuthal spinning motions. A relatively large size vortex is observed near the relatively non-sooting region of the flame edge, while a small size one is observed near the contact edge between sooting zone and OTV. The spinning frequency is about 15 Hz. Details of the spinning motions will be discussed quantitatively later.
As compared with the spinning nonpremixed flame in the von Kraman swirling flow [194], where external spinning boundary condition was applied by rotating the plate, the spinning motions observed here under AC electric field does not have external rotating boundary. The spinning direction could be either clockwise or counterclockwise. Physical mechanism on the spinning mode is not clear and requires future study.

**Flame response map**

Overall mapping of each instability mode discussed above with respect to applied $V_{ac}$ and $f_{ac}$ is provided in Fig. 5.11. As mentioned previously on the deposition of soot at the nozzle tip (Fig. 5.2b), the regimes are varying with time after applying electric fields. Thus the regimes after 10 and 300 s in applying electric fields are presented. The result shows that flame responses can be categorized based on ITV formation
represented by the black solid dash lines (same as the fitting curve in Fig. 5.3) since ITV alters the near nozzle hydrodynamic field significantly.

![Flame responses map at 10 s and 300 s after applying electric field.](image)

Figure 5.11: Flame responses map at 10 s and 300 s after applying electric field.

After ITV formation, either steady mode such as the one shown in Fig. 5.1c or unstable modes such as flickering and spinning modes can occur depending on applied $V_{ac}$ and $f_{ac}$. One mode shown here not described before is the transition mode, which can not be fully characterized by each reported mode alone. For example, flames can have pinch-off flicking motions while the flame bottom also tends to spin. The transition mode shows hybrid characteristics of other modes thus was not introduced independently. Also note that spinning mode defined allowing small amplitude of oscillations in flame height as long as the dominant motion is spinning.

The dependence of each mode on $V_{ac}$ and $f_{ac}$ can be identified from the map. For example, steady mode occupied mainly the low $f_{ac}$ region and also in high $f_{ac}$ and low $V_{ac}$ region. Flickering and pinch-off modes show a preference for $f_{ac}$ 1000 Hz. Either increasing $V_{ac}$ or $f_{ac}$ can enhance the strength of flickers and the flickering mode evolves to pinch-off mode. Spinning mode occupies a wide frequency range in
O (100 to 1000 Hz), but only for high voltage region, indicating this mode depends more on $V_{ac}$.

### 5.3.4 Electrical responses

As discussed previously regarding Fig. 5.7, the averaged power consumption $P$ obtained by integrating the instantaneous power for several cycles, could represent various flame characteristics.

As the flame instability occurs under higher $f_{ac}$, such as flickering mode, associated oscillations are usually at 10 Hz level. In order to characterize these oscillatory motions with power signals, integration of the instantaneous power needs to conduct over a much small time interval to guarantee enough temporal resolution over the flame dynamics. Take flickering mode occurring at $V_{ac}=1.5$ kV and $f_{ac}=1500$ Hz for example, associated voltage, current, and instantaneous power are shown in Fig. 5.12. The voltage and current signals have nearly 90 degree phase shift, indicating the role of the capacitor effect in the system. Resulting instantaneous power $P(t)$ shows a frequency doubling effect due to the phase shift between $V_{ac}$ and $f_{ac}$. 

For $P(t)$ oscillating about 3000 Hz in this example, sampling the power with a high resolution, i.e., 1000 Hz, can be achieved by integrating $P(t)$ with 0.001s time interval (3 power oscillating periods) from $\hat{P}(t) = \int_{t}^{t+n/f_{ac}} P(t)dt$, where $n$ is the number of periods in integrating $P(t)$. Comparing to the integrated power $\bar{P}$ shown in Fig. 5.8 about 1s interval, $\hat{P}(t)$ here is of appreciable shorter integration interval than $P(t)$. In the following, the potential of temporally averaged $\hat{P}(t)$ to correlate with associated flame transient dynamics will be tested.

In Fig. 5.13, flame height normalized by the baseline flame height $H'$, mean luminosity determined from high speed images normalized by the baseline flame mean luminosity $L'$ and also $\hat{P}(t)$ are plotted together for both flickering (a) and pinch-off mode (b) at 1.5 kV, 1500 Hz and 2.5 kV, 1500 Hz respectively. Note that mean luminosity is defined by dividing the summation of the pixel intensity of high speed images over the total pixel number and introduced here as an approximate indicator for the dynamics of the heat release rate by assuming the flame surface area is
proportional to the soot luminosity. Uncertainty involving in this assumption can be referred to [195]. For the pinch-off mode, two flame heights can be defined as high tip and low tip as shown in Fig. 5.9 b. Various number of periods in determining $\mathcal{P}$ has been tested and $n = 12$ could provide optimal condition. For the flickering mode (a), the normalized flame height, mean luminosity, are synchronized well along with $\hat{P}(t)$, although some scatters in $\hat{P}(t)$ due to the small amplitude of flame oscillations.

![Figure 5.13: Height, mean luminosity and power variation under flickering and pinch-off mode.](image)

For the pinch-off mode, the normalized low tip height, luminosity, and $\hat{P}(t)$ synchronized very well, while the normalized high tip failed in matching the crest of $\hat{P}(t)$. This implies that the power variation is well correlated with flame surface area (reasonably proportional to flame height) and isolated pocket of flame zone after pinch-off minimally affects the electrical characteristics. The effectiveness of the mean luminosity in correlating $\hat{P}(t)$ could be explained as following. Most luminosity signals are from the blackbody radiation of the soot particles. When flame is only flickering, soot particle is confined by the OH layer and the luminous area is proportional to the flame surface area, to the production rate of charged particles, thus to the power consumption rate by the flame under AC electric field. Even when the pinch-off occurs, the detached luminous part is still surrounded by the OH layer [196] thus keeps to
contribute to the power consumption rate. Defined high tip overestimated the flame surface area when detachment of the flame occurs by neglecting the quenching area between the detached flame and the main flame body. Low tip is better in predicting the real flame surface area but still not consider the contribution from the detached luminous flame to the power consumption.

For spinning flames, flame height fluctuates only slightly. For the dynamics behavior of the instability, the edge distance of yellow luminous zone from the center axis, \( R \), at several heights above the jet nozzle, \( Z \), was monitored during the spinning motion and the result is shown in Fig. 5.14. Five different \( Z \), from 2 to 4 cm are selected and resulting temporal variations of \( R \) are shown. An increased phase lag as referenced to \( Z = 2 \) cm is noted as \( Z \) increases, implying the spinning motion is initiated near the flame base and the downstream region is following the upstream region. This is consistent with the observation that AC dominantly alters the near nozzle flow fields. Spinning frequencies remain almost unchanged with time elapse and the characteristic frequency of spinning mode is about 15 Hz. Note that a typical spinning frequency of premixed flames was about 30 Hz. 

![Figure 5.14: Flame spinning motions.](image)

The flame height \( H' \) and luminosity variations along with \( \hat{P}(t) \) are shown in Fig. 5.14c. The flame length variation is small (less than \( \pm 2.5 \) percent during spinning).
While the luminosity variation is fairly large (say $\pm 2.5$ percent, which can be attributed to the view factor of the photodiode during the spinning or asymmetrical flame surface. The result of $\hat{P}(t)$ does not exhibit clear dependence on flame height and luminosity having the value of about 0.004 W with some scatters. This is understandable since the reasonably same shape of flame is rotating along the azimuthal direction.

These result of $\hat{P}(t)$ having a good correlation with flame size for the flickering, pinch-off, and spinning modes since ions production rate is reasonably proportional to the reaction zone area $[5]$. This also indicates that $\hat{P}(t)$ can be utilized as a monitoring signal of flame responses.

5.4 Concluding Remarks

We investigated both the dynamical and electrical responses of small laminar coflow diffusion flames under AC electric fields. Detailed formation process of ITV via increasing fac were revealed to be from dramatically to smoothly triggered as Vac decreases. Complete distributions of flame response modes were also provided with respect to Vac and fac at different residence time. Several instability modes induced by electric fields were newly found, including flickering, partially pinch-off and spinning modes. Related dynamics and vortical structures were explored via high speed imaging and Mie scattering techniques.

Electrical signals, including the voltage, current and power consumption were also measured simultaneously with the flame dynamics. Integrated power signal with one second time interval was successful in characterizing the subtle flame property variations across the ITV formation. With much shorter integration time length under high frequency AC, integrated power could still be correlated with unstable flames motions of flickering, pinch-off and spinning modes, indicating its potential to
be utilized as an indicator for flame dynamical responses.
Chapter 6

Small Coflow Diffusion Flame under Low Frequency AC Forcing

6.1 Introduction

Combustion instabilities are usually not desired by increasing vibration (noise) level, enhancing heat transferred to chamber walls, and inducing thermal acoustic instability that may result in a system failure [179, 197, 200]. Motivated by acoustic instability from lean premixed combustion in stationary gas turbines for low NO\textsubscript{x} emission, many studies have been conducted on premixed flames subject to external flow disturbances to understand associated thermal acoustic properties [201, 207]. Such efforts are less severe for nonpremixed flames [181, 208, 211] even though many aircraft engines or liquid fueled combustors are operated in nonpremixed flame mode.

To suppress in-phase coupling between pressure oscillation and heat release rate fluctuation and to change thermal acoustic resonance mode, passive measures of combustor geometry or fuel injection system modification are usually required [44]. Such approach is costly and has been known to be effective only within limited operating conditions [44]. Controlling methods based on actuators, such as loud speakers and micro fuel jets, can be more flexible in modifying thermal acoustic properties at required operating conditions. Once combined with feedback sensors, advanced active
control system could be further devised \[14,179\].

Associated drawbacks in this approach are that relatively large power is required to drive traditional actuators and multiple sources of time lags exist between the action of actuator and associated flame responses thus complicate the design of control system \[186\].

Electric field can be considered as a viable actuator. Flames are under weakly ionized plasma states \[5\], abundant charged particles (mainly $CH_3^+$, $H_3O^+$, $HCO^+$, $C_3H_5^+$, and electrons) are generated in a reaction zone through chemi-ionization and subsequent ion chemistry \[1,6,7\]. Under external electric field, these charged particles can be accelerated by the Lorentz force. Collisions between accelerated charged particles and neutral molecules result in momentum exchange and lead to bulk flow motion of the ionic wind effect \[88\]. The acceleration of charged particles starts immediately when electric field is applied. While certain residence time called collision response time is required for the ionic wind effect to be developed \[10,83,102,105,212\]. Accelerated charged particles acquire drift velocity enhancing diffusion and kinetic energy enhancing reaction associated with charged particles. Typically, the ratio of power consumed by electric field to heat release rate of flame is in the order of $10^{-3} \[10\].

Several studies have pioneered in the potential of DC in modulating premixed flames. Volkov et al. \[103\] explored the flame transfer function (FTF) in a flat premixed flame. Appreciable alternations of FTF were noted in the super-saturation (secondary ionization) region of the voltage current characteristic curve. Kuhl et al. \[104\], based on the high-speed imaging of the chemi-luminescence from a flame, observed that under DC the duration of flame oscillations driven by acoustic waves was modified up to 54%. Effects of DC over thermal acoustic properties of bunsen flames were also explored previously \[206,213\]. However, such investigations are still limited for nonpremixed flames.

Alternating current (AC) electric fields have shown to be effective in controlling
various flame properties even when the effect of DC was minimal \[70,84\]. For example, AC was noted to trigger toroidal vortices in the near nozzle area while DC equaling the peak voltage (both positive and negative) of AC has minimum effect as shown in Chapter 4. Exploring the potential of applying AC in controlling thermal acoustic properties of nonpremixed flames is rare. Comparing to DC, AC induced electrical pressure oscillations mimic the ones induced by acoustic waves in sinusoidal wavy profiles even though detailed interaction processes are different. For example, in nonpremixed flames, acoustic waves propagate firstly from the actuator to the edge of the diffusion layer surrounding main reaction zone. Then, the velocity perturbations induce fluctuations in reactant concentrations that further penetrate into the diffusion layer and become sensed by the reaction zone finally \[214\]. Comparatively, AC electric field exerts Lorenz force over charged particles within the reaction zone directly and could induces flow perturbation locally \[92\].

Due to the difference and similarity between velocity perturbations induced by AC electric fields and by acoustic waves, investigations on flame responses under AC forcing could improve the understanding not only in electric fields assisted combustion, but also in the utilization of AC in modulating thermal acoustic features of diffusion flames.

Recently, AC were found to be triggering toroidal vortices in near nozzle region in coflow diffusion flames under certain electrical conditions as shown in Chapter \[4\]. To avoid the influence from such dramatic change in flow fields and chemical species distributions, this paper mainly limited AC in the low frequency region (up to 200 Hz) away from AC triggered toroidal vortices. Forcing strength was adjusted via the applied voltage from 0 - 5 kV (rms). Flame responses were investigated via high speed imaging along with simultaneous measurements on electrical signals.
6.2 Experiment

The apparatus, similar to our previous chapter, consisted of a coflow burner and flow controllers, a power supplier unit, electrical monitoring circuit, and visualization systems. The coflow burner had a central fuel nozzle with an i.d. of 10.8 mm, thickness (d) of 1.0 mm and the length of 855 mm in order for the flow inside to be fully developed. The coflow air passed through plastic beads and a ceramic honeycomb for the flow velocity to be reasonably uniform over i.d. 150 mm exit. The fuel nozzle was protruded 9.6 mm above the honeycomb. Except the fuel nozzle, all other parts were made of acetal resin to provide electric insulation.

The fuel used was propane (>99.5%) and compressed air was used as the oxidizer. Mass flow controllers were calibrated with a displacement type calibrator (Bios, Definer 220). The fuel and air velocities were 1.40 and 6.2 cm/s, respectively, corresponding to a typical small laminar diffusion flame which did not exhibit flickering instability for the baseline flame without applying electric field.

The AC power unit consisted of an amplifier (TREK, 30/20A) and a function generator (NF, WF1973), which supplied sinusoidal waveform. The applied voltage ($V_{ac}$) and frequency ($f_{ac}$) were 0 - 5 kV (rms) and 0 - 200 Hz, which were in a reliable working regime of the power amplifier. The high voltage output was connected to the nozzle. A stainless mesh, with the same diameter as the coflow honeycomb, positioned at 27 cm above the fuel nozzle tip serving as the ground electrode.

The electrical monitoring circuit consisted of a 1000:1 voltage probe (Tektronics, P6015A), a current amplifier (Stanford Research System, SR570), and a high bandwidth oscilloscope (Tektronics, TPS 2014B). The high voltage probe was attached to the nozzle to measure the applied voltage and electric current was measured at the ground side with the current amplifier. A common ground is shared by all equipment to assure the same ground potential. Electric signals were processes using MATLAB. In all test cases, electric field was applied after 10 minutes operation of the baseline
flame for reasonable thermal equilibrium state of the burner system to be achieved.

The visualization setup consisted of a high-speed camera (Photron, SA4), a digital camera and a micro-lens. Flame dynamic responses could be captured with sufficient resolution. The exposure time was fixed at 1/2000 s unless otherwise specified.

6.3 Results and Discussion

6.3.1 Amplitude responses

The formation of vortical structures in the near-nozzle region of a coflow diffusion flame have been reported previously, to exclude such appreciable alteration in the flow structure, experiments were conducted with electrical conditions below such conditions of vortex formation.

Direct photos of flames during one period of oscillations at various \( f_{ac} \) from 4 to 24 Hz for fixed \( V_{ac} = 2.5 \) kV are shown in Fig. [6.1]. The nozzle tip position is marked with the solid red lines. The heights of flame tip and of dark zone in the first image in each row are selected as the reference heights represented by the white and yellow dash lines, respectively. Multiple peaks in the flame tip height (\( H_T \)) can be identified during one period of oscillations for \( f_{ac} = 4, 6 \) and 24 Hz. For 12 Hz, only one peak is observed with large amplitude of oscillation, while the amplitude of oscillation is small for other frequencies. Since the dark zone height oscillates with much smaller amplitude, flame height oscillation will be the focus in the following.
Figure 6.1: Direct photos of flame oscillations at $f_{ac}$ from 4 to 24 Hz and $V_{ac} = 2.5$ kV.

The flame luminosity, $L_F$, is also utilized, which is defined as the summation of intensity of all image pixels. In premixed flames, chemi-luminescence has used as an indicator of heat release rate except for high strain, large curvature or near extinction conditions \[215\--\217\]. In nonpremixed flames, the light emissions from flame chemi-luminescence and blackbody radiation of soot could also be adopted as a qualitative indicator for oscillating dynamics of heat release rate \[195\]. Thus, the flame luminosity
can be an indicator of the dynamics of the global heat release.

Transient behaviors of normalized values of $H'_T = H_T/H_0$ and $L'_F = L_F/L_0$ with respect to the normalized time $t' = t \times f_{ac}$ are plotted in Fig. 6.2, where the subscript 0 is for the case of the baseline flame without applying electric field and $t$ is the time at various $f_{ac}$ from 2 to 50 Hz for $V_{ac} = 2.5$ kV. For all cases, normalized applied voltage $V'(t')$ has the same phase, represented by the blue dash line marked in the 2 Hz case. Here, $V' = V_{ac}/V_0$ and $V_0$ is the peak value of applied voltages. Especially, the phase delay between $V'(t')$ and the amplitude variation $A'(t')$ ($A$ denotes either $H_T$ or $L_F$) are of interest and will be discussed later.
Figure 6.2: Responses of $H_{T}'$ and $L_{F}'$ with respect to $t'$ at various $f_{ac}$. Blue cycle line: $H_{T}'$, red triangle line: $L_{F}'$.

For $f_{ac} \leq 6$ Hz, both $L_{F}'$ and $H_{T}'$ exhibit complicated patterns having bimodal behavior at $f_{ac} = 2$ and 6 Hz and tri-modal at $f_{ac} = 4$ Hz. At $f_{ac} = 7$ Hz, the tip height clearly shows bimodal behavior while the luminosity does not show this behavior.
clearly, indicating the transition to a nearly sinusoidal pattern. As \( f_{ac} \) increases to 12 Hz, only nearly sinusoidal profile can be observed, consistent with the observation in Fig. 6.1 with large amplitude variation. For \( 18 \leq f_{ac} \leq 24 \) Hz, while the luminosity \( L'_F \) remains nearly sinusoidal, the bimodal patterns reappear in \( H'_T \), with \( L'_F \) oscillating with relatively larger amplitude than that of \( H'_T \). Further increasing \( f_{ac} \) up to 50 Hz, both \( H'_T \) and \( L'_F \) oscillates nearly sinusoidal.

The oscillation amplitude, \( \Delta A' \), defined as \( A'_{max} - A'_{min} \), are shown in Fig. 6.3 as a function of \( f_{ac} \). According to Figs. 6.2 and 6.3, the flame amplitude responses can be categorized into four modes. In mode I (for \( f_{ac} < 8 \) Hz), both \( H'_T \) and \( L'_F \) mainly respond to AC showing frequency doubling or tripling behavior and having similar amplitude variations. In mode II (for \( 8 \) Hz \( \leq f_{ac} < 18 \) Hz), the two indicators have nearly sinusoidal profiles and with similar trend in amplitude variations. In mode III (for \( 18 \) Hz \( < f_{ac} \leq 32 \) Hz), \( L'_F \) remains the sinusoidal profile with decreasing \( \Delta A' \) as \( f_{ac} \) increases. While, \( H'_T \) shows steadily increasing amplitude. In mode IV (for \( f_{ac} > 32 \) Hz, both \( H'_T \) and \( L'_F \) show nearly sinusoidal oscillation profiles with deceasing amplitude \( \Delta A' \) as \( f_{ac} \) increases.
In addition, four characteristic $f_{ac}$ can also be identified from Figs. 6.2 and 6.3 at 6, 12 and 18 Hz corresponding to local maximum and minimum points in $\Delta H_T'$ and 4 Hz having frequency tripling for both indicators. The burner has the fuel nozzle with the inner diameter of about 1 cm. In such cases, previous studies on buoyancy-driven instability has the oscillation frequency of about $f_{buoy} = 12$ Hz, when the flow rate is increased [3]. This implies that although the baseline flame is stationary, applied electric field could trigger buoyancy-driven instability. The four frequencies of 4, 6, 12, and 18 correspond to 0.33, 0.5 and 1.5 times of $f_{buoy}$, respectively.

This is an interesting behavior when compared with the flame response with acoustic forcing for naturally oscillating nonpremixed flames [218]. A lock-in phenomenon was observed by the interaction of acoustic forcing frequency and natural frequency of buoyancy driven instability. The present result, although the baseline flame is stationary, once electric field is applied, a buoyancy-driven instability is generated,
whose frequency is interacting with electrical forcing frequency, resulting in frequency doubling and tripling phenomena.

The overall amplitude of oscillation except for the frequency doubling peak at $f_{ac} = 6$ Hz, increases with $f_{ac}$ up to 12 Hz and then decreases, especially for $L'_F$, which supports the buoyancy-driven instability. The decreasing amplitude over 12 Hz needs further attention. For premixed flames under acoustic forcing, a flame response amplitude has also been observed to decrease with increased forcing frequency, which is known that a flame acts as a low pass filter to acoustic waves even though buoyancy effect is secondary [202]. For the present nonpremixed flames, the perturbation by electric field is expected to be dominantly on flow field, that is the ionic wind effect, which requires a developing time known as collision response time. As $f_{ac}$ increases, the developing degree of ionic wind decreases, which, together with the shift from the resonance between buoyancy and ionic wind, could explain the decreasing amplitude observed for $f_{ac} \geq 12$ Hz in region IV [83].

The response of flame amplitude on applied voltage $V_{ac}$ is examined as shown in Fig. 6.4 at $f_{ac} = 6$ Hz and $V_{ac} = 2.5$ kV. Both $H_T'$ and $L_F'$ are plotted by varying $V_{ac}$ from 2 to 5 kV during two periods of oscillation with voltage signal $V'$ marked as the blue dash lines for the 2 kV case. The bimodal oscillation pattern remains as $V_{ac}$ increases. As $V'$ increases, the amplitude of $A'$ increases and the amplitudes of higher peaks grow in faster rate than the lower one.

In Fig. 6.4b, $\Delta A'$ is plotted with respect to $V_{ac}$. When $V_{ac}$ is smaller than, say 2.5 kV, the dependence of $\Delta A'$ on $V_{ac}$ shows a reasonably linear relation. Considering that the variation in the phase delay between $A'$ and $V'$ with $V_{ac}$ was nearly negligible (Fig. 6.4h), the linear dependence of $\Delta A'$ on $V_{ac}$ enable the application of flame transfer function (FTF) under AC electric field forcing, which is similar to the linear FTF of premixed flames under acoustic forcing [202]. The detailed study on FTF of the present nonpremixed flames by AC forcing will be a future study.
For $V_{ac} > 2.5$ kV, a quadratic increase in $\triangle A'$ can be identified also in Fig. 6.4. Such increase does not reach a saturation in $\triangle A'$ within the range of $V_{ac}$ tested. Note that $\triangle A'$ is larger than 0.3 near 5 kV, indicating over 30% variation from the baseline flame. This substantial modifications in flame height, or heat release rate, substantiate a potential of utilizing AC in modulating a flame.

![Figure 6.4: Flame response at 6 Hz with respect to various $V_{ac}$. Blue cycle line: $H_T'$, red triangle line: $L_F'$.](image)

6.3.2 Phase diagram and spectral analysis

The amplitude $A'$ and its variation with time $dA'/dt$ are analyzed in a phase space, where is widely adopted in time delay embedding approach in analyzing a chaotic system [219]. Note that $dH_T'/dt$ is the nondimensional speed of flame tip. In Fig. 6.5 limit cycle behaviors are shown in the phase diagrams at various $f_{ac}$ with fixed $V_{ac} = 2.5$ kV (a-f) and at two voltages with fixed $f_{ac} = 6$ Hz (g,h).
The limit cycle for 4 Hz (a) shows two crossings indicating the frequency doubling tripling behavior (one crossing is at smallest amplitude region marked with the arrow, e.g., represented by a knot like shape in the blue luminosity plot. Frequency doubling behaviors are clearly shown in (b) and (c) with one crossing , and for (e) for the flame height (marked as the arrow). When $V_{ac}$ is varied (g and h), the general geometric structure in the phase space remains unaltered, implying that a basic flame response under AC electric field is mainly dependent on $f_{ac}$. In cases of 12 and 50 Hz (d and f), the maximum $dA'/dt$ appears for $A'$ reasonably close to 1, which corresponds to the baseline flame state without applying AC forcing.

The distinction between $H'_T$ and $L'_F$ can be identified by the magnitude of $dA'/dt$. For example, in Fig. 6.5 d and f, the maximum variations of $dA'/dt$ are about 10 (non-dimensional unit) for both the height and luminosity, while that of luminosity is only about 2 and the height is about 10 at 50 Hz (f), indicating that $H'_T$ is responding more sensitively on AC electric fields at this frequency. The supplementary movie shows that the bulk yellow luminous region is reasonably quasi-steady at 50 Hz while flame tip is still capable to respond to AC with noticeable amplitude. This explains
why, $\Delta H_T'$ was larger than $\Delta L_F'$ in mode IV in Fig. 6.3. Note that $H_T'$ is also capable of representing more wave information as compared with $L_F'$ even at lower $f_{ac}$. For example, at $f_{ac} = 24$ Hz (Fig. 6.2 and Fig. 6.5e), a bimodal pattern can only be observed for $H_T'$. The number of crossing in the phase space is summarized in Fig. 6.6 with respect to $f_{ac}$ at $V_{ac} = 2.5$ kV (a) and with respect to $V_{ac}$ at $f_{ac}=6$, 12, and 24 Hz (b). One and zero crossings can be identified, For $18$ Hz < $f_{ac}$ ≤ $24$ Hz only the height shows the crossing. For 6 and 12 Hz, the number of crossing does not vary with applied voltage (b), while for 24 Hz, the number of crossing decreases from one to zero as $V_{ac}$ increases from 3.5 to 4 kV. as the reason can be identified from the inset figure. As $V_{ac}$ increases over 3.5 kV, the non-monotonic behavior between two peaks disappears. This transition behavior will be discussed later.

Spectral analysis was further conducted on $H_T'$ and $L_F'$ applying fast Fourier transformation (FFT) for $V_{ac} = 2.5$ kV by varying $f_{ac}$ and the result is shown in Fig. 6.7. From the FFT result (inset in Fig. 6.7a), the relative amplitude in the frequency space of FFT at $f_R = f_{ac}$, 2$f_{ac}$ and 3$f_{ac}$ are plotted in Fig. 6.7a. For $f_R = f_{ac}$, the amplitudes for both $H_T'$ and $L_F'$ have peaks at at 12 Hz. Similar local peaks can also be observed at $f_R = 2f_{ac}$, which may be due to the artifact in FFT. For $f_R = 2f_{ac}$, another peak can be identified at 6 Hz, corresponding to 0.5 $f_{buoy}$, with

![Figure 6.6: Crossing quantity dependency on $V_{ac}$ and $f_{ac}$.](image_url)
the amplitude comparable to the that for $f_R = f_{ac}$, an indication of the bimodal patterns. Similarly, for $f_R = 3f_{ac}$, first peak occurs at $f_{ac} = 4$ Hz with an amplitude comparable to that for both $f_R = 2$ and $3f_{ac}$, corresponding to the frequency tripling behavior. This behavior implies that as the AC frequency becomes the buoyancy oscillation frequency multiplied by the integer, the detailed flame response is lock-in to the buoyancy oscillation frequency by frequency doubling and tripling behavior.

The FFT analysis also shows that the flame height and luminosity behaviors for $f_R = f_{ac}$ resembles the amplitude behavior shown in Fig. 6.3. A complete picture of the flame response of $H'_T$ with respect to $f_{ac}$ are shown in Fig. 6.7b. The monitoring conditions shown in Fig. 6.7a are represented by the white dashed lines. Major flame responses all concentrate for the three harmonics. For $f_{ac} > 6$ Hz, the amplitude of the main harmonics at $f_R = f_{ac}$ always dominates, indicating the occurrence of frequency lock-in phenomenon. Complicated nonlinear wave interactions, such as beat frequency $|f_{ac} - f_{buoy}|$ appearing in buoyant flames under acoustic forcing, could not be observed here.

The spectral analysis is again applied over $H'_T$ at 6 and 24 Hz with $V_{ac}$ ranging
from 1 to 5 kV. The amplitude responses at \( f_R = f_{ac} \), \( 2f_{ac} \) and \( 3f_{ac} \) with respect to \( V_{ac} \) are shown in Fig. 6.8. The amplitudes at \( f_R = f_{ac} \) and \( 2f_{ac} \) increase with comparable proportion at \( f_{ac} = 6 \) Hz while that of \( f_R = f_{ac} \) is much larger than the one of \( 2f_{ac} \) at 24 Hz. The role of buoyancy could explain such difference. As electric field is applied, the charged particles within the flame gain kinetic energy from the electric field and diffuse the gained energy to neutrals resulting in the ionic wind. At low \( f_{ac} \), the residence time required for this energy diffusion process is small comparing to \( 1/f_{ac} \), thus the velocity perturbations induced by the electric field should be at the \( f_{ac} \) in the kinetic point of view. For example, without buoyancy, flame must mainly oscillate at 6 Hz if \( f_{ac} \) is of such value and only an enhanced flame flicker with the same frequency should be expected as \( V_{ac} \) increases. When buoyancy is introduced, the second harmonic \( f_R = 2f_{ac} = 12 \) Hz is close to \( f_{buoy} \) thus the resonance tends to occur between the flame dynamics at the second harmonic and buoyancy. As a regard, the flame dynamical motions, originally only occurring at \( f_R = f_{ac} \), is redistributed among \( f_R = f_{ac} \) and \( f_R = 2f_{ac} \) during the interaction with the buoyancy. This explains why the amplitude response at \( f_R = f_{ac} \) is similar to that of \( f_R = 2f_{ac} \) in Fig. 6.8a as \( V_{ac} \) increases. Situation is different, however, at \( f_{ac} = 24 \) Hz since resonance effect between the wind effect and buoyancy is weak thus only the flame response at \( f_R = f_{ac} \) determined by the ionic wind dominates as \( V_{ac} \) increases. In Fig. 6.6b, when \( f_{ac} = 6 \) Hz , similar amplitude responses occur at \( f_R = f_{ac} \) and \( 2f_{ac} \) thus bimodal behaviors could maintain with respect to \( V_{ac} \). For \( f_{ac} = 24 \) Hz, resonance is weak thus the response at \( f_R = f_{ac} \) becomes much larger than that of \( f_R = 2f_{ac} \) as \( V_{ac} \) increases, resulting in the decreased crossing number from 3.5 kV to 4 kV.
6.3.3 Flame phase responses

A phase delay between heat release rate and acoustic forcing is one of the key parameters to be determined in order to construct FTF of flames, which is important in adjusting oscillating phase of heat release rate and decoupling it from pressure fluctuations.

Two types of phase delays could be identified in Fig. 6.2. One is between $H'_T$ and $L'_F$ and the other between $L'_F$ and $V'$ denoted as $\theta_{LV}$. The result in Fig. 6.2 showed that the delay between $H'_T$ and $L'_F$ is small. A sensitive dependence of $\theta_{LV}$ on $f_{ac}$ can be easily identifiable in Fig. 6.2. For example, by comparing 6 and 7 Hz cases, only 1 Hz increase in $f_{ac}$ results in a substantial shift in $\theta_{LV}$.

Exact values of phase delay are typically determined by the cross correlation method. However, appreciable nonlinearity introduced by the buoyancy in $L'_F$ makes this method not proper. Thus, $\theta_{LV}$ was determined based on the time difference between the trough locations between $L'_F$ and $V'$. Other methods, such as calculating the phase difference between $L'_F$ and $V'$ in frequency space obtained via FFT, have also been tested. The method based on the peak location provided most physically meaningful data, while FFT based method provided similar trend.
Before exploring the quantitative analysis of $\theta_{LV}$, it is illustrative to understand the origin of phase delay between heat release rate and velocity perturbations ($\theta_{HV}$) in nonpremixed flames under acoustic forcing. Taking counter flow nonpremixed flame for example, $\theta_{HV}$ consists of three components [44, 214]: (1) the time for pressure wave to propagate from an actuator to the region ahead of a flame, (2) pressure wave induced velocity perturbations convert to the fluctuation of mole fractions of reactants at the edge of a diffusion layer, and a certain time required for such fluctuations to penetrate through the diffusion layer and reach the reaction zone, and (3) the time required for reaction zone to response to the molar concentration fluctuations.

Under electric fields, situations can be much different. Chemi-ionization occurs mainly near a main reaction zone corresponding to chemi-luminescence zone (without considering soot and PAHs which can locate in the diffusion layer for nonpremixed flames). The number density of charged particles decreases as moving out of the zone due to fast recombination between charged particles [1]. Once electric field is applied, ions accelerated by the fields collide with neutrals and develop ionic wind (convective flows), which can be initiated near the reaction zone. This ionic wind induced pressure oscillations or say velocity perturbations are sensed subsequently by other regions in the hydrodynamic field. Applying AC electric field eliminates the coupling process between velocity perturbations and the transport or chemical processes in nonpremixed flames, as compared with acoustic wave forcing cases thus simplify the modulating process on heat release rate.

Although ionic wind is responsible for driving velocity perturbations, the cause of $\theta_{LV}$, however, cannot be explained solely by the ionic wind effect. For example, if the time required for the ionic wind to develop ($t_{ionic}$) is responsible for $\theta_{LV}$, a similar $t_{ionic}$ may be expected regardless of $f_{ac}$ since $t_{ionic}$ is mainly determined by kinetic nature of flames. As shown in Fig. 6.9a, the time delay between the luminosity oscillations and applied voltage signals decreases quickly as $f_{ac}$ increases and maintains about 2
ms level over 80 Hz. The order of magnitude of time could reach up to 150 ms at $f_{ac} = 2$ Hz. Thus, other factors seems to be responsible for this large difference.

Figure 6.9: Time and phase delay analysis at various $f_{ac}$ fixed at 2.5 kV.

The quantitative value of $\theta_{LV}$ with respect to $f_{ac}$ are plotted in Fig. 6.9b with the phase shift limited within $[-180^\circ, 180^\circ]$. Two different regions can be identified. For $f_{ac} < 80$ Hz, $\theta_{LV}$ varies appreciably with $f_{ac}$, while it maintains a constant value of $90^\circ$ for $f_{ac} > 80$ Hz. Also for $f_{ac} < 80$ Hz, several characteristic $f_{ac}$ can be identified at 2, 4, 6 and 12.5 Hz corresponding to $\theta_{LV}$ near $90^\circ$, 90$^\circ$, $-180^\circ$, and 0$^\circ$, respectively. Note $f_{buoy}$ is about 12 Hz (exactly at 12.5 Hz with refined frequency data, although not shown here), thus 2, 4, and 6 are all sub-harmonics of $f_{buoy}$. It is reasonable to speculate the phase delay observed should also be attributed to
the coupling between buoyancy and oscillatory heat release rate driven by AC. For example, the zero $\theta_{LV}$ is observed at $f_{ac} = f_{buoy} = 12.5$ Hz, where the flame oscillation is maximized having a resonance mode, such that buoyancy oscillation is in phase with the heat release rate (luminosity). The ability of AC in adjusting the phase delay between buoyancy and heat release rate implies that electrical forcing could be a promising viable method in controlling buoyancy induced instabilities observed in lifted nonpremixed flame \[151, 220, 221\]. For $f_{ac} > 80$ Hz, $\theta_{LV}$ remains a constant value of $90^\circ$, indicating that buoyancy effect becomes minimized at high $f_{ac}$ thus not contributing to the phase delay anymore. This is also supported by the supplementary movie 1 within that flame body could be noted to ceases oscillation thus experienced buoyancy is also quasi-steady. As shown in Fig. 6.9a, time delay in this saturation region is noted to between 1 2 ms, similar with $t_{ionic}$ reported previously for premixed flames under DC electric fields \[105, 212\].

After demonstrating the importance of buoyancy in determining $\theta_{LV}$, a comparison is made between nonpremixed flame under fluctuating velocities induced by acoustic forcing and by AC electrical forcing (AC). Due to limited experimental data of a stable coflow nonpremixed flame under acoustic forcing, $\theta_{LV}$ under AC electric field is compared with $\theta_{HV}$ of the planar nonpremixed flame under velocity perturbations reported in \[214\]. As shown in Fig. 6.9a, $\theta_{LV}$ is established near at $90^\circ$ even at quite low $f_{ac}$, such as 2 Hz. But under velocity perturbations, heat release rate oscillates nearly in phase ($\theta_{HV}$=0) with the velocity perturbations for $f_{ac} < 10$ Hz. As $f_{ac}$ increases, $\theta_{LV}$ shifts rapidly between $-180^\circ$ and $180^\circ$ and reaches a saturation value near $90^\circ$ for $f_{ac} > 80$ Hz. Comparatively, $\theta_{LV}$ under counterflow nonpremixed flow varies much slowly with respect to the oscillating frequency of velocity, denoted as $f_v$. For example, for $f_v$ varying from 10 to 200 Hz, $\theta_{HV}$ only changes from $0^\circ$ to about $50^\circ$. The high sensitivity of $\theta_{HV}$ over $f_{ac}$ indicates the promising potential of applying AC electric fields to adjust the phase angle of heat releases rate within a wide range.


6.3.4 Electrical responses

Normalized current $I'$, defined as $I_{ac}/I_0$, under the same frequency conditions as in Fig. 6.2 are plotted with respect to normalized time $t'$ in Fig. 6.10 as the red lines. Here, $I_{ac}$ is the measured temporal current and $I_0$ is the positive maximum value of the current. The voltage variation $V'$ is denoted by the blue dashed line, shown for the 2 Hz case, which is used as a reference in determining the time delay, $\theta_{VI}$, between $V'$ and $I'$. In addition, normalized instantaneous power consumption $P'$, defined as $P_{ac}/P_0$, is also shown as the solid blue line. Here, $P_{ac}$ is the instantaneous power, defined as $P_{ac} = V_{ac} \times I_{ac}$, and $P_0$ is the maximum positive value of $P_{ac}$. The instantaneous power $P'$ profile is similar for other $f_{ac}$ cases, thus only shown in 2 Hz case. For reference, the values of $I_0$ and $P_0$ are plotted in Fig. 6.11 as a function of $f_{ac}$. 
Figure 6.10: Voltage, current and power behavior at various frequency fixed at 2.5 kV.
Two properties of $I'$ require further clarification. First, the positive and negative values of $I'$ can be asymmetric with respect to the zero current, especially at low $f_{ac}$. For example, for $f_{ac} = 2$ Hz, the magnitude of peak negative current is about three times larger than that of the positive one. This asymmetric current behavior is named as the current diode effect observed under DC [10], arising from the differences in mass and mobility between positive and negatively charged particles in a reaction zone as will be shown in the next chapter. Note that positively charged particles are ions, while negatively charged particles are composed of negative ions and electrons. An index $\phi$, defined as $\Delta I / \Delta I_s$, as inserted figure in Fig. 6.12a, is introduced to represent the degree of the diode effect. Here $\Delta I$ is the oscillating amplitude of the current profile and $\Delta I_s$ is the difference between the symmetric location of the current profile and the zero value. This will be discussed later. Second, due to a capacitor effect in electric circuit as shown in Chapter 5, an appreciable phase delay in $\theta_{VI}$ can exist and it explains the frequency doubling effect appearing in $P'$ shown in Fig. 6.10 at 2 Hz. Due to the existence of both $\phi$ and $\theta_{VI}$, a direct utilization of $I_{ac}$ as an indicator for a flame property, as suggested previously with DC electric
field [1][186][222], could be misleading in AC. For example, when $I_{ac}$ is maximized, flame surface area (heat release rate), or say the ion production rate, is not necessarily maximized (such as 12 Hz shown in Fig. [6.2] and [6.10]).

Quantitative values of both $\phi$ and $\theta_{VI}$ are plotted in Fig. [6.12a], inside $-90^\circ$ phase shift and $\phi=0$ are marked by red dash line and blue dash dot dot line respectively. As $f_{ac}$ increases, $\theta_{VI}$ asymptotically approaches to $-90^\circ$ at which the electric circuit will consist only of a capacitor. The value of $\phi$, denoting the strength of the diode effect, increases from -10\% (minus sign means negative current is larger than the positive one) towards 0 (vanishing diode effect). This can explain why the current asymmetry is widely observed in DC but not in high frequency AC conditions [10][82][92].

The behavior of power consumption is represented in Fig. [6.12b] for the average power consumption integrated over during 1 s, $\overline{P}$, along with the power consumption during one cycle $P_p$, equalling $\overline{P}/f_{ac}$. It can be noted that as $f_{ac}$ increases, $\overline{P}_p$ calculated from $V_{ac}$ and $I_{ac}$ decreases. Three parameters determine the characteristics of $I_{ac}$, peak current $I_0$, $\theta_{VI}$, and $\phi$. As $f_{ac}$ increases, $I_0$ increases as shown in Fig. [6.11] and this results in increased $\overline{P}_p$. However, $\theta_{VI}$ approaches $-90^\circ$ during the process and tends to decrease $\overline{P}_p$. Although $\phi$ is also varying from -0.1 to 0 during the process, it will not contribute to $\overline{P}_p$ as long as $V_{ac}$ is symmetric with respect to zero value. In this regard, the decreasing trend of $\overline{P}_p$ with respect to $f_{ac}$ is the competing result of $I_0$ and $\theta_{VI}$. Situation is different, however, for $\overline{P}$ since there are actually more periods within one seconds due to increased $f_{ac}$. In Fig. [6.12b], averaged power consumption $\overline{P}$ still shows monotonic increasing trend. If limiting the range of $f_{ac}$ within 30 Hz, corresponding $\overline{P}$ is only at the level of $1 \times 10^{-3}$W. Known that the heat release rate of the baseline flame is about 100 W as shown in Chapter [4], AC electric field is capable to perturb the heat release rate up to 30\% with power consumption smaller than 0.01\% of the heat release rate.
6.4 Concluding Remarks

Under low frequency AC forcing with electrical conditions not generating toroidal vortices, responses of flames were further investigated. Several nonlinear flame responses, including frequency doubling and tripling phenomena, were identified. Spectral analysis revealed that such nonlinear responses were attributed to the combined effects of triggering buoyancy-induced oscillation of the flame as well as the ionic wind generated by applying AC. Phase delay behaviors between the applied voltage and the heat release rate (or flame size) were also studied to explore the potential of applying AC in controlling flame instability. It was found that the phase delay had large variations for AC frequency smaller than 80 Hz and became saturated at over 80 Hz, which has been explained based on the interaction between the buoyancy and ionic wind. Electrical measurement showed the power consumed by the AC was smaller than 0.01% of the heat release rate from the flame, indicating the economical advantage of applying electric field as a viable actuator.
Chapter 7

Electrical Current Response in Thin Ionized Layer with External DC: Effects of Relative Position and Mobility of Charged Particles

7.1 Introduction

Electrically-assisted combustion to control many aspects of a flame has been an interesting research area for many decades. Charged particles of positive and negative ions and electrons are generated in a flame zone through chemi-ionization along with subsequent ion chemistry. External electric fields could influence the movement of charged particles, through which various aspects of combustion can be modulated, including flame stability [73, 74, 83, 103, 107, 187], flame propagation speed [10, 60, 63, 71, 223], and emissions [99, 110, 111, 224].

Among the effects of electric fields on a flame, a modification of flow field by an ionic wind has been extensively investigated [9, 34, 83, 89, 92, 187], which is generated by momentum transfer to neutral molecules through collision from accelerated charged
particles with the Lorentz force under external electric fields. Such an ionic wind effect can be associated with the variation in electrical current responses when external electric fields are applied.

Typically when an external DC field is applied, an electrical current from a flame has a quadratic dependence on electric fields. Then it becomes saturated with excessive DC field over certain critical field intensity \([1, 5, 92, 186]\). In the sub-saturated regime having quadratic increase in current, a redistribution of space charges to minimize their potential shields an electric field and limits the current. While in the saturated regime, no further space charges are left in a flame zone such that all the generated ions and electrons migrate toward corresponding respective electrode. In such a case, the saturated current is limited by the rate of charged particle generation in a flame \([5, 92]\). This saturated current can be understood as an intrinsic property of a flame with a given mixture, temperature, pressure, and flow conditions.

In the sub-saturated regime, since the current response due to the separation of charged particles from a flame is a result of local field intensity, a generalized trend of the ion current with respect to external electric field cannot be obtained. As an example, when the polarity of DC field to a flame is changed, one might observe a drastic change in the current even with the same external voltage \([1, 10, 75, 225, 226]\). Such different response of the ion current with respect to the polarity of DC sometimes is referred to as a flame diode effect \([10]\). However, due to the lack of rigorous approaches to explain the current behavior in the sub-saturated regime, many observations regarding this regime and consequent difference in flame responses still remains to be clarified. In this regard, a simplified model has been developed and a complementary experiment has been performed to explore the characteristics of electrical current from a thin ionized layer under DC fields. In particular, difference in current behavior with different polarity in the sub-saturated regime will be elucidated.
7.2 Simplified Model and Simulation

A simplified model considered an ionization layer in one-dimensional space, with the coordinate \( x \) having the domain of \([0, L]\), where \( L \) is the distance between two parallel electrodes, as schematically shown in Fig. 7.1. It is a transient-diffusive system with charged particle generation. In the modeling of the drift-diffusion transport of charged multi-species with the ionization source under external electric fields, charged particles are grouped into three: positive ions, negative ions, and electrons.

![Figure 7.1: Schematic of flames tested.](image)

The derivation of governing equations was based on the simplified model in a previous work \cite{92}, where only the ions were considered for the analysis of current behavior with flames. While in the present study, for the reason that a flame contains appreciable portion of electrons among negatively charged particles, the governing equations were extended to accommodate the large difference in the mobilities between ions and electrons. The interaction of charged species with background neutrals was neglected.

The generation of charged particles through chemi-ionization in a flame was modeled having a spatial Gaussian profile as the source terms on the basis of a local iso-thermal assumption of reaction zone. The Poisson equation for electrostatic potentials was coupled with the charge transport equations. The resulting governing
equations are as follows. Positive ions:

\[
\frac{\partial n_+}{\partial t} + \frac{\partial}{\partial x} \left[ -D_+ \frac{\partial n_+}{\partial x} - K_+ n_+ \frac{\partial V}{\partial x} \right] = k_i g - k_r n_+ (n_e + n_-) \tag{7.1}
\]

Negative ions:

\[
\frac{\partial n_-}{\partial t} + \frac{\partial}{\partial x} \left[ -D_- \frac{\partial n_-}{\partial x} - K_- n_- \frac{\partial V}{\partial x} \right] = (1 - \alpha) k_i g - k_r n_+ n_- \tag{7.2}
\]

Electrons:

\[
\frac{\partial n_e}{\partial t} + \frac{\partial}{\partial x} \left[ -D_e \frac{\partial n_e}{\partial x} + K_e n_e \frac{\partial V}{\partial x} \right] = \alpha k_i g - k_r n_+ n_e, \tag{7.3}
\]

Electric potential:

\[
\frac{\partial^2 V}{\partial x^2} = -\frac{q_e}{\varepsilon} (n_+ + n_- + n_e), \tag{7.4}
\]

Spatial profile of ionization:

\[
g = \exp \left[ -\frac{\pi (x - H)^2}{a^2} \right], \tag{7.5}
\]

where \( t \) is the time, the subscripts +, −, and e represent the positive ions, negative ions, and electrons, respectively, \( n \) is the number density of charged species carrying a unit charge \([1.227,227]\), \( K \) is the mobility, \( D \) is the diffusion coefficient, \( k_i \) is an ionization rate, \( k_r \) is the recombination rate, \( V \) is the electric potential, \( H \) is the center of the ionized layer, \( a \) is a thickness parameter in the Gaussian profile of the ionized layer, \( q_e \) is the unit charge \((1.6 \times 10^{-19} C)\), \( \varepsilon \) is the vacuum permittivity \((8.854 \times 10^{-12} C/V - m)\), and \( \alpha \) is the ratio of electrons among the negatively charged species ranged between 0 to 1. The mobilities of charged species, and the kinetic rates for ionization and recombination are to be described in Section 4.1.

The boundary conditions at \( x = 0 \) and \( L \) are, \( V(0, t) = V_a, V(L, t) = 0, n_k(0, t) = 0 \) and \( n_k(L, t) = 0 \), where \( V_a \) is the electric potential applied to the electrode located
at $x = 0$.

The above system of equations was solved with the ordinary differential equation solver of ODE23t in the MATLAB software using the method of lines (MOL) approach. A constant reconstruction over each cell on clustered grid points near the boundaries and the location of ion source [92]. A grid independence test suggested that 200 computational grid points were sufficient to resolve the domain of interest.

### 7.3 Experiment

To substantiate the result with the model, a counterflow burner experiment was conducted. A thin disk shaped diffusion flame (modeled as ionized layer) could be stabilized in quasi one-dimensional electric fields. The diameter of nozzle was 10 mm and the separation distance between two nozzles was 10 mm. At the exit of each nozzle, a thin perforated disk having a hole-density of 79/cm$^2$ with 800 µm in hole diameter was placed to establish a quasi one-dimensional electric field, which are connected to a power supply [99].

In order to form a diffusion flame between the two nozzles (also the electrodes), methane and oxygen streams diluted with nitrogen were injected through the upper and lower nozzle, respectively. By changing the initial mole fractions of methane and/or oxygen at the nozzle exits, the position of diffusion flame relative to the lower nozzle can be adjusted [228].

To stabilize a diffusion flame near the center, the mole fractions of methane ($X_{CH_4}$) and oxygen ($X_{O_2}$) were set to be 0.171 and 0.389, respectively, which were balanced with nitrogen. The two streams have the same mean jet velocity of 20 cm/s. A direct photo of such a flame is shown in Fig. 7.2a, exhibiting a planar diffusion flame stabilized in the counterflow burner. While higher $X_{CH_4}$ and smaller $X_{O_2}$ are necessary to locate a flame closer to the oxidizer nozzle (lower nozzle) [228]. To
achieve an appreciable contrast in flame location, the mean jet velocities were also changed to 30 cm/s and 10 cm/s for the fuel and oxidizer, respectively (Fig. 7.2b). Detailed experimental conditions are listed in Table 7.1. Overall mixture composition in the flame zone due to the diffusion of the reactant was designed to be $CH_4/O_2/N_2 = 1/2/8$ for all tested flames in Table 7.1. This leads to have the same adiabatic flame temperature, thus the generation of ions in a unit volume of the flames could be maintained reasonably the same for the two flames.

![Schematic of flames tested.](image)

**Figure 7.2:** Schematic of flames tested.

<table>
<thead>
<tr>
<th>H/L</th>
<th>Upper Nozzle</th>
<th>Lower Nozzle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$X_{CH_4}$</td>
<td>$X_{O_2}$</td>
</tr>
<tr>
<td></td>
<td>$X_{N_2}$</td>
<td>$U$ [cm/s]</td>
</tr>
<tr>
<td>0.49</td>
<td>0.171</td>
<td>0.829</td>
</tr>
<tr>
<td>0.21</td>
<td>0.271</td>
<td>0.729</td>
</tr>
</tbody>
</table>

Coaxial nitrogen sheath flows surrounding the jets were supplied to minimize outside disturbance and to suppress a parasitic secondary diffusion flame with ambient air. The mean flow velocity of the nitrogen sheath was matched with that of the corresponding central jet to suppress unnecessary effect of shear layer between the
central jet and the sheath flow. The flow rates of gases were controlled with mass flow controllers. The nozzles were water-cooled to maintain the temperature of fuel and oxidizer to be consistent.

A set of a power supply (Trek, 10/10B-HS) and a function generator (NF, WF1973) applied DC electrical potential to the lower nozzle, while the upper nozzle was grounded. An oscilloscope (Tektronics, DPO 2024) was used to monitor voltage and current characteristics. A 1000:1 voltage probe (Tektronics, P6015A) measured applied voltages and an additional resistor of 100 kΩ was placed in series between the upper nozzle and the ground to measure the current. The voltage across the resistor was converted into current, which was corrected with respect to an internal resistance (1kΩ) of a voltage probe (Agilent, 10070C).

It was assumed that the location of ion generation through chemi-ionizations reasonably coincides with a flame front. A blue colored layer, which is due to a chemiluminescence of CH radicals, is known as a reasonable indicator for a flame front. Thus, the brightest axial locations of the blue flames in Fig. 7.2 were considered as the locations of the thin ionized layers when the model is validated with the experiment.

7.4 Results and Discussion

The observed asymmetric current behavior [4, 10, 75, 225, 226] with respect to the polarity of applied DC to a flame may be attributed to a distortion of local electric field due to a skewed position of an ionized layer toward one electrode and/or large difference (three orders) in the mobility between electrons and ions. These will be discussed in the following.
7.4.1 Ionized Layer at the Center of a Gap

Electrical current behavior when a thin ionized layer is located at the center between the electrodes (H/L=0.5) is analyzed first. Two extreme cases with $\alpha = 0$ (all negative charges are carried by negative ions) and 1 (those are carried by electrons) are examined to test the effect of different mobility. Here, the mobilities of both the positive and negative ions are adopted as $2.9 \times 10^{-4} m^2/s \cdot V$ [225,229], while that of electrons as $0.4 m^2/s \cdot V$ [230]. The width parameter $a$ of the ion generation profile $g$ is set to be 1 mm, to approximate typical flame thickness. Ionization rate $k_i$ is chosen to be $1 \times 10^{20}/m^3 \cdot s$ [1] and recombination rate $k_r$ to be $2.4 \times 10^{-13}/m^3 \cdot s$. The current density is plotted against the mean field intensity defined as $V_a/L$ in Fig. 7.3.

Figure 7.3: Computed voltage current characteristic curve under $\alpha = 0$ and 1.

The simulated result captures the typical characteristics of ion current in the sub-saturated regime having a near quadratic increasing trend for low field intensity (best quadratic curve fit are marked as the dotted lines). The result also predicts the saturated regime for high field intensity. Because a saturated current depends only on the rate of ion generation, the saturation current is independent of the type
of negative charge carriers $\alpha$. Comparing the cases between $\alpha=0$ and 1, the rate of increase in the current density is much faster with field intensity with $\alpha=1$ than that of the case with $\alpha=0$.

The difference in the mobility of negatively charged particles (between negative ions and electrons) could result in a change in the distribution of space charges between the source of charges and the anode. Consequently, locally modified field intensity due to space charge redistribution could lead to different dynamic response of the movement of charged particles. In this regard, the local field intensity $E$ is plotted against $x/L$ in Fig. 7.4 for $V_a = \pm300V$.

![Computed electric field spatial distribution for $\alpha = 0$ and 1, $V_a = \pm300V$ when $H/L = 0.5$.](image)

Figure 7.4: Computed electric field spatial distribution for $\alpha = 0$ and 1, $V_a = \pm300V$ when $H/L = 0.5$

As shown in Fig. 7.4, local field intensities with $\alpha = 1$ are about two times higher than those with $\alpha = 0$. Such stronger local field result in the aforementioned faster rate of increase in the current density with $\alpha = 1$ compared to the case of $\alpha = 0$. The local field intensities, however, show mirror profiles with respect to the location of the ionized layer regardless of $\alpha$ for different polarity of applied DC. This
can be attributed to the fact that the ionized layer is located at the center between two electrodes, such that asymmetrical current characteristics cannot be observed for different polarity of applied DC.

### 7.4.2 Skewed Ionized Layer Location

The current density behavior is further analyzed when the ionized layer is located away from the center toward either one of the electrodes. Figure 7.5 shows the result for $H/L = 0.25$ and 0.75 with $\alpha = 0$ and 1. When ions carry all the negative charges ($\alpha = 0$), the profiles are symmetric with the polarity.

![Figure 7.5: Computed voltage current characteristic curve for $H/L = 0.25$ and 0.75 with $\alpha = 0$ and 1](image)

While the current density exhibited asymmetric behavior with respective to the polarity for $H/L = 0.25$, when electrons carry all the negative charges $\alpha = 1$. For the case with $H/L = 0.75$, which is a conjugate condition of $H/L = 0.25$ with respect to the central plane of symmetry, steeper increase in the current is found when the energized electrode, which is farther from the ionized layer, applies positive potentials
to the ionized layer.

Thus, the result in Fig. 7.5 shows plane symmetry behavior in the electrical current behavior for the cases of $H/L = 0.25$ and 0.75. This can be interpreted that in the case with a skewed ionized layer, when the electrical potential of a closer electrode to the ionized layer is lower than that of the farther electrode, more rapid increase in the electrical current can be obtained.

The effect of $\alpha$ is further tested at several values of $\alpha$ in Fig. 7.6 with $H/L=0.25$. For $V_a/L > 0$, the dependence of $\alpha$ on the current behavior is small. While for $V_a/L < 0$, there is a drastic change in the current behavior. As the applied negative potential to the energized electrode increases for a specified $\alpha$, e.g. $\alpha = 0.4$, the current increases rapidly first just like the case of $\alpha = 1$, and then increases rather slowly similar to the case of $\alpha = 0$.

![Figure 7.6: Computed voltage current characteristic curve for $H/L = 0.25$ with $\alpha$ from 0 to 1 with 0.2 interval](image)

The bifurcation point where the current behavior starts to branch out from the trend of $\alpha = 1$ is marked in the figure with black open dot. The normalized critical current for each tested $\alpha$ at the corresponding bifurcation point with the saturated
current is reasonably matched with the portion of electrons out of negative charge carriers, i.e., $\alpha$.

In this regard, we plotted the respective contributions of ions and electrons to current density in Fig. 7.7 for the case of $\alpha = 0.4$. The result shows that as $V_a/L$ decreases in the negative voltage range, the current density follows the behavior for $\alpha = 1$ until the contribution by electrons are saturated. Further increase in the current with increased negative $V_a$ beyond the critical point is attributed to the negative ions. This indicates that the faster moving electrons migrate first from the ionized layer, followed by slower moving negative ions. Note that in the positive potential region, no significant variation can be found. However, the detailed bifurcation characteristics are the same as the cases in the negative potential region.

![Figure 7.7: Computed respective contributions of ions and electrons to voltage current characteristic curve at $H/L = 0.25$ with $\alpha = 0.4$ and 1](image)

To further elucidate the effect of the difference in the mobility between ions and electrons and the skewed flame position on the asymmetric current behavior, the local electrical potential $V$ and the field intensity $E$ are plotted against $x/L$ in Fig. 7.8 and 7.9. Two cases with $V_a = 300V$ and $-300V$ were compared when the ionized layer is
located at $H/L = 0.25$. To better explain this result, we introduced a thickness of the zone between the ion source and the anode ($\delta_-$) as shown in Fig. 7.8 which is ideally filled with negative charges with a bias voltage. Likewise, $\delta_+$ indicates the thickness between the source and the cathode having positive charges. The subscript NP indicates negative potential applied to the energized electrode, while PP represents positive potential to the energized electrode.

![Graph showing electrical potential spatial distribution](image)

Figure 7.8: Computed electrical potential spatial distribution at $H/L = 0.25$ with $\alpha = 0$ and 1 and $V_a = \pm 300V$ respectively.

When $\alpha = 0$, since the mobilities of positive charge carrier (positive ion) and negative charge carrier (negative ion) are the same, the moving speed of each charge carrier from the source toward corresponding electrodes is the same for the same field intensity. Thus, the number density of the negative ion in the zone between the source and the anode is the same as that of the positive ion in the region between the source and the cathode. Consequently, the absolute value of the local potential shows a point-wise symmetric behavior centered at the position of the ionized layer ($x = 2.5mm$), regardless of the polarity. This can be confirmed with symmetric local
field intensities shown in Fig. 7.9 for the case of $\alpha = 0$. Therefore, with $\alpha = 0$, the rates of increase in the current are the same irrespective of the polarity as shown in Fig. 7.5.

Figure 7.9: Computed electrical field spatial distribution at $H/L = 0.25$ with $\alpha = 0$ and 1 and $V_a = \pm 300\text{V}$ respectively.

On the other hand, when $\alpha = 1$, due to faster moving electrons, the number density of electrons in the region between the source and the anode is much smaller than that of the positive ion in the region between the source and the cathode. Clearly, this resulted in the less significant potential drop in the zone between the source and the anode ($\delta_-$) than that in the other zone ($\delta_+$). As a counter effect, a compensation of potential drop ($V_a$) must occur in the other region between the source and the cathode ($\delta_+$). In this reason, when the negative external potential is applied to the energized electrode, which is closer to the ionized layer than the other, the field intensity ($V_a/\delta_{+,NP}$) could be enhanced, which is greater than $V_a/\delta_{+,PP}$ with a positive external potential. Such intensified local field intensity due to faster moving electrons is clearly demonstrated in Fig. 7.9. This leads to asymmetric behavior of the rate of increase in the current reported in the previous studies [4,10,75,225,226]
Recalling the result in Fig. 7.3, the symmetrical increase of electrical current was predicted even with \( \alpha = 1 \), when the ionized layer locates at the center of the gap between two electrodes \( (H/L = 0.5, \ H = 5\text{mm}). \) Due to the centered ionized layer, the thicknesses between the ion source and the cathode are the same regardless of the polarity of DC as \( \delta_{+,NP} = \delta_{+,PP} = 5\text{mm}. \) Thus, the local field intensity along the gap has to be plane symmetry with respect to the center of the gap (Fig. 7.4). As a result, no asymmetric current behavior could be found with the centered ionized layer.

On the basis of above results, the difference in the mobilities play a key role to increase the sensitivity of electrical current to an external voltage, when the relative electrical potential of a closer electrode to the ionized layer is lower than that of the other electrode.

### 7.4.3 Model Validation with Counterflow Diffusion Flames

To test the model with the experiment, calculations were performed with \( H/L = 0.49 \) and \( 0.21 \) to simulate the experimental conditions as in Table 7.1. The case with \( H/L = 0.49 \) was chosen to simulate the case of a centered ionized layer, while that of \( H/L = 0.21 \) is representing a skewed ionized layer to the energized electrode. A visible flame width was monitored at each applied voltage and the projected area of the flame to the electrode was used to convert measured electrical current into a current density.

When the flame is located near the center, the present model reasonably well predicts the current behavior when using \( \alpha = 1 \) as shown in Fig. 7.10, demonstrating near symmetric current increase on polarity. In the case of the flame position shifted closer to the energized electrode \( (H/L = 0.21) \), asymmetric increase in the current due to polarity change could be observed experimentally. The present modeling with
$\alpha = 1$ reasonably well predict the experimental asymmetric current behavior rather than the case with $\alpha = 0$. This implies that most of negative charges is carried by electrons in flames or flame generated negative ions can be much small as compared to positive ions, since no significant change in the current behavior with negative DC was found comparing the result in Fig. 7.6.

Figure 7.10: Comparison between experimental and computed voltage current characteristic curve at $H/L = 0.49$ with $\alpha = 0$ and 1.

However, our model gives an over-prediction with negative external potentials and an under-prediction with the positive ones. This discrepancy in the electrical current with $H/L = 0.21$ can be attributed to the uncertainty in determining the location of the charge source as well as the area of it, because the blue chemiluminescence is not necessarily to be matched with the location of of maximum concentration of charged species. It has been reported that charged species are abundant at a location away from the maximum concentration of CH radicals, where the blue luminosity shows its peak [1].

Concerning the flame area, which was used to analyze the current density in Fig.
the uncertainty with the area of the charge source is expected to be small, since the modeling and the experiment show good agreement in the case of $H/L = 0.49$.

Next, to clarify the influence of the location of the ionized layer on the current behavior, simulations were conducted with $\alpha = 1$ for various $H/L$. As shown in Fig. 7.11, as $H/L$ increases from 0.21, the current profile rotates in a counter-clockwise direction. Comparing with the experimental data of $H/L = 0.21$, it may be speculated that the location of corresponding ionized layer may be further away from the energized electrode.

![Figure 7.11: Comparison between experimental and computed voltage current characteristic curve at $H/L = 0.49$ with $\alpha = 0$ and 1.](image)

When $|V_a/L| > 0.3\text{kV/cm}$ in Fig. 7.11, small deviation of experimental data from simulation with $H/L = 0.35$ can be found. This might be due to the relocation of the flame while increasing the applied voltage. During the experiment, the flame slightly moved toward cathode due to Lorentz force acting on it. Although such variation in the flame location was less than 0.2 mm with $V_{700V}$, it may influence the current.

As a result, it may be concluded that the discrepancy between the model and
experimental result in Figure 8 in the current behavior with $H/L = 0.21$ may be partially attributed to the discrepancy between the exact location of the ionized layer in a flame and the brightest luminous zone. However, because the effect of electric field on diffusion flames also can significantly alter the structure of a flame\textsuperscript{99}, further detailed flame simulation coupled with Poisson equation including ion-chemistry needs to be done in near future.

7.5 Concluding Remarks

Present modeling highlights the behavior of electrical current with an external electrical potential to a thin ionized layer. Due to faster moving electrons than positive ions, a major potential drop occurs in the region between an ion source and a cathode. When the ionized layer is off-centered, the distance between the ion source and the cathode will be different with respect to the polarity of applied DC. Therefore, approximate effective electric field intensity scaled as an external applied voltage divided by the distance between the ion source and the cathode ($V_a/\delta_+$) can be stronger with a shorter $\delta$ depending on the polarity of DC. In this reason, asymmetric current increase occurs for different polarity showing more rapid increase in the current with a negative external potential to an electrode, which is closer to a thin ionized layer than the other. The present modeling is also qualitatively verified comparing with the experimental result using counterflow diffusion flames.
Chapter 8

Concluding Remarks

8.1 Summary

We have studied the effects of AC electric fields over small nonpremixed jet flames to explore the potential of AC as an alternative actuator in designing the future combustion control system. Both experimental and numerical techniques have been adopted.

The main contributions are summarized in the following:

- Flow characteristics in small coflow diffusion flames were investigated with a particular focus on the near-nozzle region and on the buoyancy force exerted on fuels with densities lighter and heavier than air (methane, ethylene, propane, and n-butane). The flow-fields were visualized through the trajectories of seed particles. The particle image velocimetry technique was also adopted for quantitative velocity field measurements. The results showed that the buoyancy force exerted on the fuel as well as on burnt gas significantly distorted the near-nozzle flow-fields. In the fuels with densities heavier than air, recirculation zones were formed very close to the nozzle, emphasizing the importance of the relative density of the fuel to that of the air on the flow-field. Nozzle heating influenced the near-nozzle flow-field particularly among lighter fuels (methane and ethylene).
Numerical simulations were also conducted, focusing specifically on the effect of specifying inlet boundary conditions for fuel. The results showed that a fuel inlet boundary with a fully developed velocity profile for cases with long tubes should be specified inside the fuel tube to permit satisfactory prediction of the flow-field. The calculated temperature fields also indicated the importance of the selection of the location of the inlet boundary, especially in testing various combustion models that include soot in small coflow diffusion flames.

- Experiments were performed by applying sub-critical high-voltage AC to the nozzle of laminar propane coflow diffusion flames. Light scattering, laser-induced incandescence and laser-induced fluorescence techniques were used to identify the soot zone, and the structures of OH and polycyclic aromatic hydrocarbons (PAHs). Particle image velocimetry was adopted to quantify the velocity field. Under certain AC conditions of applied voltage and frequency, the distribution of PAHs and the flow field near the nozzle exit were drastically altered, leading to the formation of toroidal vortices. Increased residence time and heat recirculation inside the vortex resulted in appreciable formation of PAHs and soot near the nozzle exit. Decreased residence time along the jet axis through flow acceleration by the vortex led to a reduction in the soot volume fraction in the downstream sooting zone. Electromagnetic force generated by AC was proposed as a viable mechanism for the formation of the toroidal vortex. The onset conditions for the vortex formation supported the role of an electromagnetic force acting on charged particles in the flame zone.

- Dynamical and electrical responses of coflow diffusion flames under AC electric fields were investigated with a particular focus on the onset conditions of inner toroidal vortices. High speed imaging was adopted to study the dynamical responses of flames and the detailed vortical structures were revealed via
Mie scattering techniques. The onset condition for the formation of ITV was found to be very sensitive to frequency for relatively high voltage cases. Several new instability modes induced by electric fields were found, including flame flickering, partial pinch-off and spinning modes. Related dynamics and vortical structures were explored via high speed imaging and Mie scattering techniques. Electrical responses, including the voltage, current and power consumption were measured simultaneously with the flame dynamics. The integrated power signal successfully indicated a sudden jump across the onset of ITV formation. Under high frequency AC, integrated power could be correlated with unstable flames motions of flickering, pinch-off and spinning modes, indicating its potential to be utilized as an indicator for flame dynamical responses.

- Under low frequency AC forcing for the electrical conditions without generating toroidal vortices, responses of flames were further investigated. Several nonlinear flame responses, including frequency doubling and tripling phenomena, were identified. Spectral analysis revealed that such nonlinear responses were attributed to the combined effects of triggering buoyancy-induced oscillation of the flame as well as the ionic wind generated by applying AC. Phase delay behaviors between the applied voltage and the heat release rate (or flame size) were also studied to explore the potential of applying AC in controlling flame instability. It was found that the phase delay had large variations for AC frequency smaller than 80 Hz and became saturated at over 80 Hz, which has been explained based on the interaction between the buoyancy and ionic wind. Electrical measurement showed the power consumed by the AC was smaller than 0.01% of the heat release rate from the flame, indicating the economical advantage of applying electric field as a viable actuator.

- A simplified model was developed to better understand electrical current re-
responses when external electric field is applied to a flame. A flame zone was modeled as a thin ionized layer. Model governing equations were derived from species equations by implementing mobility differences depending on the type of charged particles, especially between ions and electrons. The result showed that the sub-saturated current along with field intensity was significantly influenced by the polarity of DC due to the combined effect of non-equal mobility of charged particles as well as the position of the ionized layer in a gap relative to two electrodes. When an electrode, which is closer to the ionized layer, is applied negative DC, rapid increase in current can be achieved compared to the case of applying positive DC to the same electrode. Experimentally measured current using counterflow diffusion flames agreed qualitatively well with the model predictions.

8.2 Future Works

Based on the works mentioned above, following works need further study in the future:

- While the importance of nozzle heating and fuel density effects have been emphasized in this thesis, the role of these effects in nonpremixed jet flames with moderate Reynolds number are still not clear. It is expected that when the jet velocity is high, the near nozzle flow structure is expected to have secondary effect in controlling the global flame dynamics. This speculation may fails as the near nozzle buoyancy effect becomes dominant when the fuel density increases or nozzle temperature increases (such as high pressure condition) thus systematic studies are required.

- Inner vortical structure has been noted to be triggered by AC and an explanation based on electromagnetic force has also been provided in this thesis. However, several vital questions still remain: 1) most important charged particles
in contributing to the strong ionic wind effect observed and 2) non-dimensional numbers controlling ITV formations. Tests with different nozzle diameters may answer the second question.

- Flame oscillations, including flickering and partially pinch-off modes, have been identified under AC. However, the exact physical mechanisms to explain these unstable modes are still unclear. Clarifications on these mechanisms could be beneficial in designing an efficient controlling system modulating buoyancy driven combustion instability.

- Correlations between the measured electrical signals and flame dynamics indicate the possibility to use the integrated power resulting from applying AC as the indicator of the combustion states. It can serve as a feedback signal in designing a feedback control system. Active feedback control system can be an important topic in the future.

- One dimensional current prediction simulation is limited by various assumptions adopted. However, the essence of this simulation is that detailed ion-chemistry might not be necessary in qualitatively predicting dominant flame dynamical and electrical responses associated with the ionic wind. To extend to more complicated combustion problems, it is inspiring to apply such methodology to flame simulations without ion chemistry in multi-dimensions to approach practical effects of electrical fields on flame responses.
REFERENCES


APPENDICES

A  Coflow Burner Design

Main body of the burner is design as shown in Fig. ??.

![Figure A.1: Drawing of the main body of the burner.](image)

Shroud of the burner is design as shown in Fig. ??.
Figure A.2: Drawing of the shroud of the burner.
B  Paper Published and Under Preparation


- Y. Xiong, M.S. Cha and S.H. Chung, ”Instabilities and Electrical Responses of Small Laminar Coflow Diffusion Flames under AC Electric Fields”, under preparation.

