FLAMES IN HORIZONTAL ELECTRIC FIELD, DEVIATION AND OSCILLATION

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Abstract
The current paper is an investigation on the behaviour and motion of flames in case where the flame is placed between two charged parallel metal plates with different charges. A physical experimental setup has been constructed to make precise experiments. Observations give detailed information about the deviation of the flames towards the negative plate, and in some special cases, the diffusion flames start "oscillating". Theoretical explanation has been proposed for the phenomena and has been proved by the experiments in qualitative predictions. A numerical model has also been developed based on the theory to be compared with the experimental data quantitatively. This paper is based on the original solution of team of Iran on the 3rd problem of IYPT 2011.

Introduction
Flames have been reported to be ionized gases and in some cases to be plasmas [1]. The fact of being plasma or not, depends on the flame temperature and the burning material [1].

Asymmetrical division of the flame in two branches deviating toward different plates, in case where the flame is placed between two charged parallel metal plates, has been observed and investigated in few resources. A suggested explanation is the difference in the mass of the positive and negative ions existing in the flame [2, 3]. In some investigations it is mentioned that the free electrons in the flame existing because of the ionization tend to react with the surrounding air molecules in the presence of the electric field [3].

Other investigations have been made in different experimental situations, e.g. the effect of vertical electric field on flame stability has been investigated numerically by *Belhi* et al. [4] and it has been shown that flame stability increases in the presence of electric fields due to the momentum source which exists because of the electric force exerted to the ions within the flame (ionic wind).

We will discuss the effect of ionic wind on the shape and motion of the flame in horizontal electric field, and will show that the difference of the mass of the positive and negative ions is not a crucial matter in describing the phenomenon. The oscillatory motion of the flame is also a subject of investigation, which has been initially observed by the authors and no other references as we've seen, has reported such a motion.

Theory Base

In the situation where the flame is under the effect of electric field, Aside from combustion process, some other chemical and electro-chemical reactions occur. In order to determine the electric load within the flame; which is of significant importance, these reactions must be well understood.

The first set of chemical reactions in the flame are those related to the main fuel-Oxygen reaction; a highly exothermic reaction. This reaction produces enough heat to raise the temperature to obtain the ionization energy. The second reaction is the heat thermal ionization, decomposing the molecules into positive ions and free electrons in the high temperature zone. This reversible reaction causes free electrons to flow in the boundaries of the ionized zone.

Combustion: $Fuel + O_2 \Rightarrow CO_2 + H_2O + Energy$

Ionization: $Fuel \Leftrightarrow Fuel^+ + e^-$

In the presence of the electric field the forces acting on positive ions and electrons are in opposite directions, the charge separation will occur, and the contact of the electrons with oxygen molecules increases. The electrons react with O_2 producing O_2^-, and separate from the flame [5].

Electron reaction: $O_2 + e^- \Leftrightarrow O_2^-$

After this process the total flame charge will be positive in the presence of electric field.

Flame Deviation

Considering the positive and visible part of the flame as a system, there would be an input stream of low-momentum particles resulted from the combustion process entering from the lower part of the flame, and an output stream of high-momentum cooled particles exiting from the upper part of the flame.

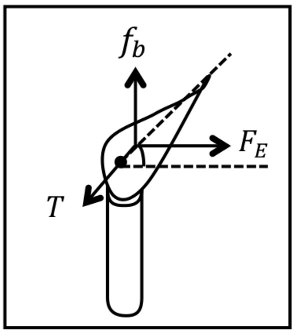

Figure 1: Applied Forces

There are three external forces applies to each particle in this system; 1) Buoyancy Force, 2) Electric Force, 3) Air resisting Force (in the case of instability). But since the system is not isolated, there would be another force applied to the system due to the difference in momentum of input and output particles. This force is in the direction of the flame, toward the lower part of the flame (Figure 1).

In the case of steady deviation, these three forces must be in equilibrium. According to what we discussed; in the presence of the electric field, as the bigger part of the flame consists of positive ions, the major part will be attracted towards the negative plate. Meanwhile as a small part in the flame consists of negative ions, a very small portion will be attracted towards the positive plate (Figure 2).

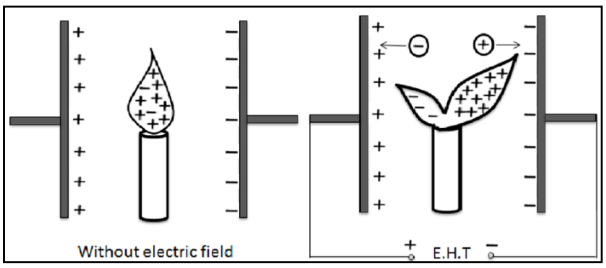

Figure 2: shape and behavior of the flame in the presence of electric field

In case of plasma flames, the distribution of the electric charges causes a significant internal electric field, cancelling the external electric field. This phenomenon is known as the collective effect [1]. ~~So in this case the plasma flame does not deviate at all.~~

Flame Oscillation

Because of being ionized, the flame is assumed to be conductive in high voltages [6] (as our experiments confirm). Thus in the case when the flame can touch the plates electrically, electrical discharge will occur and the flame will gain electrons from the negative plate, losing the positive charge. This reduces the electric force, forcing the flame to go back to its initial position. However, because of advection and the continuous combustion reactions, it will be positively charged again. Therefore the whole process will be repeated causing the flame an oscillatory motion.

Numerical Analysis

The numerical analysis of this phenomenon is based upon five assumptions; these assumptions will lead us to develop a simple model that presents us some numerical predictions of both deviation and oscillation of the flame. These assumptions are either approved in reliable resources or can be easily observed to be true or they are reasonable estimations.

We propose a simplified model for the flame based on these assumptions:

- The flame can be considered conductive in high voltages
- The flame is positively charged in electric field
- There exists an input and output electric current
- There is a force applied to the flame, in its inverse direction
- Electric and mass density are both uniform in the flame

There is an ingoing electric current, which has a constant amount (due to combustion process), and an outgoing electric current, which is proportional to the electric load of the flame. Considering these assumptions, the motion of the centre of mass of the flame was simulated using a numerical method developed in MATLAB. The Euler method was used to solve the ODE. Constants and coefficients were either measured or estimated.

Experiment Method

a) Experimental Setup

The experimental setup ~~is~~ consisted of several types of flame (candle or Bunsen burner), two parallel aluminum metal plates connected to a high voltage device with the maximum voltage of 14 KV~~s~~ and adjustment resolution of 0.1 KV. Distance between the two plates is precisely adjustable (1mm precision). In order to reach a uniform electric field around the flame, size of the plates is large enough comparing to the size of the flame (30 x 30 cm plates). The flame is placed in the middle of the two plates.

The corresponding behavior of the flame, under electric field was recorded using a high-speed camera (1000 FPS), placed exactly in front of the flame. Using this video, some precise experimental data was extracted.

b) Video Processing

The recorded video has 1000 frames per second, using MATLAB image processing tool-kit, the relative position of the center of area of the flame (estimated as the center of mass) and the wick of the candle (lower part of the flame) was found. The angle between this vector and vertical line (Deviation Angle) was measured in each frame (Figure 3). DA as a function of time and voltage was extracted from different experiments.

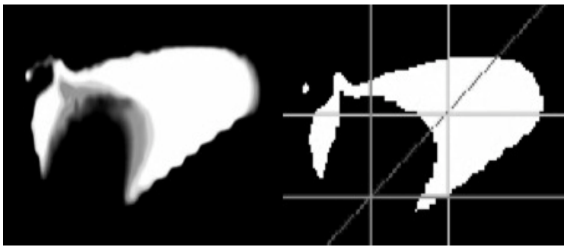

Figure 3: MATLAB image processing. Left picture: Original picture, Right picture: Processed picture

Experiment

Initially, some qualitative experiments were designed to evaluate the basic theory.

Streams of rising smoke were used in order to detect the flow around the flame while it is oscillating. Flows of negative ions toward the positive plate and also positive ions toward the negative plate; were both observed (Figure 4); which verifies the validity of ionic wind theory. These laminar flows also reject the possibility of turbulent flows as the cause of oscillatory motion.

Figure 4: Smoke Experiment

In case of oscillating candle flame, a layer of non-conductive material was placed between the flame and the plates by coating the aluminium plates, avoiding electrical discharge interaction between the flame and plates. As a result, the oscillatory motion of the flame was diminished, verifying the main reason of the oscillation as the electric discharge.

Most of the experiments were done using a candle flame, however the behavior of other flames was also observed. Pre-mixed flames mostly showed no oscillation at all. This is a result of the sufficient ionization degree, which can keep a steady current within the flame in the electrically touching condition with the plate. Some flames; e.g. the diffusion petroleum flame, were highly turbulent; and unsteady motion could be observed even in cases where no external field exists.

Three quantitative experiments were also designed, in order to compare the experimental results with the numerical model predictions. Candle flame was used in all the experiments.

a) Critical Voltage of Oscillation

According to previously proposed theoretical explanation, the “Oscillation” occurs when the flame touches the plate electrically and

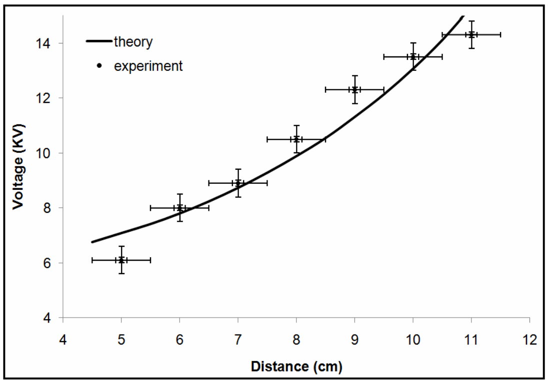

Figure 5: Critical Voltage of Oscillation

discharges. For the flame to reach the plate there is a critical deviation angle and its corresponding voltage. This voltage is a function of the distance between the plates. The less the distance is, the lower voltage is required for oscillation to occur. The critical voltage of oscillation was measured by gradually increasing the voltage in different distances between the plates.

b) Deviation Angle Vs. Applied Voltage

Before the flame starts oscillating, it deviates and reaches to a stable condition. DA is proportional to the applied voltage. By increasing the applied voltage DA will also increase. A candle flame was placed between the plates; distance between the two plates was fixed, the applied voltage was gradually increased and using image-processing method, the angle of deviation was measured in each voltage.

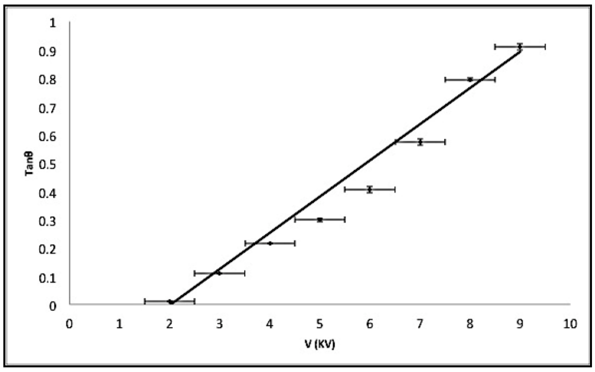

Figure 6: Deviation Angle

c) Frequency of oscillation

it was observed that the oscillatory motion of the flame has a well-defined frequency. In a fixed distance between the plates, this frequency was measured in different voltages using image-processing methods. The difference in high voltages can be because of neglecting the air resistance, which could get sufficient in high velocities.

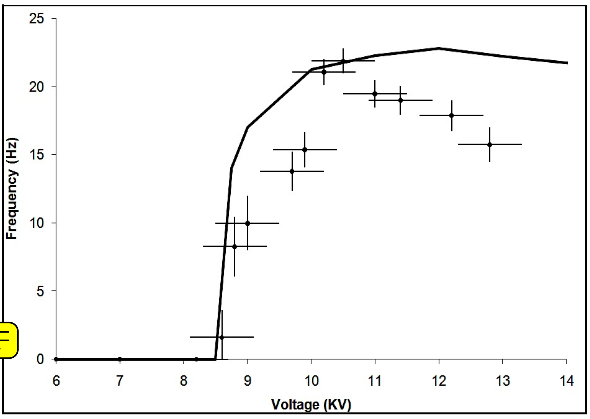

Figure 7: Frequency of Oscillation

According to the presented results of experiments, the proposed theory is verified in each step, qualitative experiments confirm the basis of the theory and well-matched results of experimental data confirm the numerical model to be an appropriate estimation.

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