Numerical Analysis of The Induced Electric Field Effects on Combustion Parameters and Reducing Emissions of Swirling Flame of Hydrocarbon Fuels

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Abstract

The aim of this study is to investigate and analyze the effects of electric field on combustion pollutants such as CO₂, NOₓ and other contaminants including Soot. The main method used for evaluation of effective parameters and variables such as temperature, voltage, intensity of rotation of air-fuel mixture and fuel-dependent variables including physical and chemical properties of fuel. The results of simulation and experiments show that the positive potential of central electrode increases the flame temperature in the combustion chamber and near the wall which means the wall is closer to the flame. By exerting the field, it was found that the percentage change in the main pollutants carbon dioxide and nitrogen oxides such as nitrogen monoxide have decreased by 8 and 6%, respectively. While the field is exerted, flame speed and subsequently flame energy has also increased. Negative polarity also increases the concentration of positive ions in the center of flame. As well as the positive polarity, reverse flow has been observed here. In a electric field of 3 kV and positive polarity, heat transfer to the walls is almost 52 percent higher than when there is no electric field.

Keywords: Electric Field, Combustion, CO₂, NOₓ, Cold Plasma, Heat Transfer, Combustion Optimization, Pollution reduction
1. Introduction

In 1957, Calocte conducted some studies with the aim of understanding the mechanism of ion formation in the flames based on thermal and chemical ionization. The results included thermal ionization mechanism, ionization resulting from electron excitation and chemical ionization. Chemical ionization is considered as a significant mechanism in the reactions inside the flame. However, in fact all these mechanisms contribute to the concentration of formed ions [1]. In a study carried out on the basis of mathematical calculations in 1985 by Nurani and colleagues, scientists numerically investigated the effect of inlet temperature and the equivalence ratio on the spray penetration, the quality of mixing, the temperature distribution and production of NO\textsubscript{X} in a Cylindrical combustion chamber cylinder with wall jet and demonstrated that by increasing the inlet temperature, NO\textsubscript{X} formed in the initial area (primary combustion zone) is reduced, resulting in a greater depth of jet penetration. As the inlet temperature increases, flow rate will increase, but in other parts of the combustion chamber, NO\textsubscript{X} increases in a sustainable way [4]. In 2003, the effect of production of green-house gases (\text{CH}_4, \text{CO}_2) resulting from the combustion of fossil fuels were studied at the University of Latvia. The purpose of these experiments was to reduce the production of combustion pollutants. The desired fuel was propane gas, and the experiment was conducted for premixed and non-premixed swirling flame. The results was that in the combustion reaction with swirling flame and a higher swirl number, the exertion of electric field has a pleasant effect on separation of carbons and soot formation and reduces the production of NO\textsubscript{X} and CO\textsubscript{2} by 25 percent and 6-10 percent, respectively [7]. In a study at the University of Juja South Korea in 2006, CO hydrogenation was extensively studied not only for the production of synthetic natural gas SNG but as a gas treatment process at a chemical plant in which CO acted as a toxic catalyst. Methane compound from CO and CO\textsubscript{2} can be produced on catalysts dependant on various metals. According to the studies presented in literature review, non-thermal plasma generated by dielectric discharge, radiation discharge or pulsed discharge facilitate most catalytic reactions such as oxidation of organic compounds and fluorinated carbon sequestration. In a similiar way, non-thermal plasma can also increase the catalytic conversion of CO/CO\textsubscript{2} inside the methane. Methanation of CO Over nickle-loaded alumina has previously been studied, which the results have shown that plasma significantly increases catalyst activity, especially in low temperatures and pressures [10]. In 2009, a study was conducted by Yoann-Nicolas Jaffre, Thomas Aka-Ngnui and Abdul Rahman.
This study aimed to determine the threshold of flame combustion to produce non-thermal plasma and optimization of different types of plasma reactor geometries for various applications of off-gases. According to the results of this study, current Selective Catalytic Reduction processes (SCR) can be optimized to reduce NOx by the non-thermal plasma behavior. NTP can not alone reduce NO produced by a heat engine to N₂ and O₂, but the oxidation of NO to NO₂ in upstream provides a common selective catalytic reduction. The efficiency of this system depends on two main parameters: the power supply and geometry. The purpose of this study, as mentioned, has been the production and optimization of plasma to control pollution in automotive heat engines [13]. Today, a combustion chamber with a high-intensity and torus swirling flame is more widely used due to greater efficacy and stability of the flame. CFD results obtained by Inessa Barmina and colleagues in 2011 indicate that controlling the degree of premix, field uniformity and flame stability limits proportionally corresponds with the level of pollution. By increasing feeding air circulation at a constant rate, it is possible to significantly increase the formation of reverse axial flow by consumption of full-fuel and limiting soot formation rate. With greater control over the way of exerting electric field, combustion parameters, using the direct effect of recirculation and the mixing rate of flame compounds these results can be achieved. All combustion parameters and the factors listed above, depends on the initial voltage and polarization of electrodes inside the chamber [16]. In one study in 2014, Emad Alidadiani numerically investigated the effects of electric field on the flame and heat transfer inside a combustion chamber using the finite element method, with two-dimensional unstructured mesh. The results indicate that exerting electric field forces over a flame with negative polarity increases the rate of heat transfer to the walls of the combustion chamber. As voltage increases, the slope of velocity profiles in one cross-section of combustion chamber increases and near the centreal line of combustion chamber the speed rises much more and near the wall, especially at the exit point, it reduces. When the polarity is negative, temperature profiles act contrary to the velocity profiles near the outlet and the temperature increases near the wall. At the end of the combustion chamber, the flame is accumulated around the central electrode and takes a sharper shape and on the whole, increases the heat transfer to the walls. The results were compared with experimental work and its authenticity has been confirmed by a good approximation [24]. In a research conducted by the maintenance and operation of the Abadan refinery in 2014, flue gas of the distillation unit was improved through corona discharge to eliminate NOx and SO₂.
At the beginning of corona discharge, current-carrying electrodes were connected to an AC power supply with a high voltage transformer. It has been observed that the distance of electrodes (5.3 and 5 mm) and the power of discharge (3, 4, 5 and 6 kV) on removal of NO, NO$_2$ and SO$_2$ has been influential. The results show that increasing the plasma discharge power results in increasing the removal efficiency of pollutants. The effects of electrodes distance on the removal efficiency of pollutants indicates that when plasma power is between 3 to 5 kV, the removal efficiency increases to its maximum and then, when the power plasma reaches 7 kV, removal efficiency decreases [27]. Another research conducted by Bijuu Patel in 2014 was aimed to use non-thermal plasma and electrical discharge technology to reduce NO$_x$, soot and organic compounds from the combustion process. The results of these investigations have led to the reduction of emissions and improvement of efficiency [28].

2. Electric Relations Governing on the Issue and Mechanism of Combustion

As a result of exerting electric field on the flame of propane gas and the air and due to the nature of flame and the existence of charged ionic variations in combustion products, the electric forces exerted on ions cause changes in dynamic and thermodynamic properties of the flame. In the Navier-Stokes Equations, apart from the term inertia on the left side of the Equation and the pressure gradient and viscosity terms on the right side, a term is also intended for the external forces acting on the fluid. By examining the electric force acting on the fluid and fixing it in Navier-Stokes Equation, one can look at the effects of this force in dynamic and thermodynamic properties of the flame.

3. Evaluation of Electric Force [33]

In order to examine the electric force acting on the fluid, we initially examine the phenomenon of ionic wind. In a electrohydrodynamic actuator located inside a gas such as air, by generating a high voltage difference between the two electrodes (usually a wired or needle-shaped electrode with an plate electrode) positive ions are formed as a result of ionization in the vicinity of an electrode with a lesser radius of curvature. These ions influenced by electric forces, while being driven from ion injective electrode (anode) to the ion collector electrode (cathode) exchange momentum with neutral fluid particles and set the fluid in motion. This induced translator motion is called ionic wind. Within the flame, due to its nature of being charged, this translator motion takes place very effective and more obvious.
The amount of electric body force per unit volume is obtained via the Equation 1. Equation 1 was obtained given the assumption that fluid polarization is linear function of electric field and depends only on the density.

\[
\ddot{f}_e = \rho_e \overline{E} - \frac{1}{2} E^2 \nabla \varepsilon - \frac{1}{2} \nabla \left[ E^2 \rho_e \left( \frac{\partial \varepsilon}{\partial \rho} \right) \right]
\]  

(1)

Where, \( E \) is electric field strength, \( \rho_e \) bulk density of electric charge, \( \varepsilon \) electric permittivity coefficient of environment and \( \rho \) density of the fluid. For ionic wind phenomenon in an incompressible gas, the only component of body force acting on the fluid would be Coulomb force. In fact, for a gas under the influence of an electric field, Equation 1 is translated into 2 Equation along the X-axis. In general, electric force is calculated by the software in two directions.

\[
\rho \frac{D\overline{u}}{Dt} = \rho_e \overline{E} - \nabla p + \mu N^2 \overline{u}
\]  

(2)

In Equation 2, \( \overline{u} \) represents the horizontal component of the fluid velocity, \( P \) is the partial pressure of the fluid and \( \mu \) is dynamic viscosity of the fluid. Given the Equation 2, it is observed that considering the electric body force, we need to obtain charge distribution and electric charge density in the fluid. To do so, we make use of Charge Conservation Law and the Gauss's law in electric field (Maxwell's Equations). The Charge Conservation charge is expressed in Equation 3.

\[
\nabla \overline{J} + \frac{\partial \rho_e}{\partial t} = 0
\]  

(3)

Where, \( J \) is electric charge density and is expressed according to Equation 4.

\[
\overline{J} = \sigma \overline{E} + \rho_e \overline{u} + \rho_e \mu_e \overline{E}
\]  

(4)

In Equation 4, \( \mu_e \) is ion mobility. The terms on the right side of Equation represent the conduction, convection and ion mobility, respectively.

4. Transfer phenomena in combustion species [40]

To calculate the ion transfer and combustion species, according to diffusion process and convection, we use 5 Equation that is the Equation of conservation of mass.

\[
\frac{\partial c}{\partial t} + u \nabla c = \nabla (D \nabla c) + R
\]  

(5)
In Equation 5, \( C \) represents species concentration, \( D \) the distribution coefficients, \( R \) the rate of reaction and \( U \) is the velocity. The first part of the left side of the Equation 5 represents the gathering or taking of species. The second part of the left side of Equation 5 is related to convective motion given the velocity profile. On the right side of Equation 5, the first part is related to diffusion translation that is the result of interaction between species and the second part is used to check the source of production or consumption of species, which is the rate of a chemical reaction. For transfer, two mechanisms of convection and conduction can be studied under the influence of an electric field that is expressed in Equation 6. If these species and ions are under the influence of electric field, the parameters related to what is stated in the section 5 are also used in Equation 5 and transfer Equation can be expressed as Equation 6. In fact Equation 6 states transfer of species under the influence of electric field.

\[
\frac{\partial c_i}{\partial t} + \nabla \left( -D_i \nabla c_i - z_i u_{m,i} F c_i \nabla V + c_i u \right) = R_i
\]  

(6)

In Equation 6, \( F \) is Faraday constant, \( V \) electric potential and \( z \) is the charge number related to ions. Ion wind phenomenon is also expressed by Equation 6.

5. Heat Transfer from the Flame[ 41]

Heat transfer can be considered as the most important goal for combustion. In fact, the main purpose of using industrial combustion is heat transfer. In this section, the concepts related to heat transfer in combustion are discussed. Heat transfer is a science that examines energy exchange between the masses. In general, three mechanisms for heat transfer can be investigated. Conduction, convection and radiation.

6. Convection in Laminar Flow (Laminar Substrate) [41]

An important factor in convective heat transfer is the laminar substrate. When a fluid passes on a solid surface, exactly on the fluid layer adhering to the surface, there is an area of flow that is known as the laminar substrate. Thermal resistance is ranging from 1% in liquid metals or molten to 95% of the total thermal resistance of the fluid. In high-turbulent flows the laminar substrate is very thin and therefore the greater the turbulence, the more the heat transfer would be. That is why in many of heat exchanger, grooved surfaces are used to increase transfer heat. Assuming that a fluid with constant temperature \((R,0)\) enters a tube, and heat transfer is done through walls done, two input areas and an advanced area are created. The length of input area is attained according to Kaeize and Craford Equation. The Equation 7 shows this area.

\[
\left( \frac{X_{the}}{D} \right) = 0.05 \text{Re. Pr}
\]  

(7)

Where, \( \text{Re} \) represents the Reynolds number, \( \text{Pr} \) Prandtl number, \( D \) the diameter of the input and \( X_{the} \) the input length.
7. Radiative Heat Flux [41]

Equation 8 expresses the radiation heat flux.

\[ q = \sum \frac{(I_i - I_j)}{A_i F_{ii}} \]  

Equation 8

In Equation 8, \( I_i \) and \( I_j \) are radiation on the surface \( i \) and \( j \) respectively, \( A_i \) the area of surface \( i \) and \( F_{ii} \) the form factor of surface \( i \).

8. Radiation in Flame [41]

Accurately estimating the flame radiation is difficult for the following reasons:

- Precise calculation of flame temperature is not possible. Only adiabatic flame temperature is clear and radiant heat transfer is the reason for the genuine flame temperature to be lower.

- Contrary to common misconceptions, radiation results from gas and solid species in the flame not the reaction itself.

- Among gas and solid species, water vapor and carbon dioxide have the most significant role in flame radiation. Due to the lack of uniformity in the concentration of this species in different parts of the flame, we observe different thermal characteristics in different directions. This also makes estimation of radiation in the flame difficult. Soot particles in the flame, that turns it into yellow, can also affect the flame radiation and given that obtaining the mass ratio of carbon particles is very difficult, estimating the amount of flame radiation becomes difficult.

9. Theoretical and Thermodynamic Bases Used for Calculation of Pollutants [46]

In calm flames and at the molecular level of turbulent flames, the formation of NOx can be attributed to four distinct chemical kinetic process: thermal formation, quick formation, fuel NOx and \( \text{N}_2\text{O} \)-mediated. Thermal NOx is formed by the oxidation of atmospheric nitrogen in the air combustion. Quick NOx is produced during high-speed reactions against the flame. Fuel NOx is generated by the oxidation of nitrogen in fuel. At high pressures and oxygen-rich conditions, NOx may also be produced from molecular nitrogen by \( \text{N}_2\text{O} \).

Note: NOx models can not be used in connection with the premixed combustion model.

10. Equations Governing the Transfer of NOx

Ansys Flunet solves mass transfer equation for a variety of NO, with respect to heat transfer, propagation, production and consumption of NO and related species. This is a thoroughly general approach that is extracted on the basis of the fundamental principle of conservation of mass.
The effect of residence time is included in NOx mechanisms (a concept of Lagrangian reference frame) through the term convective transport in the governing equations written in Euler reference frame. For thermal and quick NOx mechanisms, only NO species of transport equation is required:

\[
\frac{\partial (\rho Y_{NO})}{\partial t} + \nabla \cdot (\rho \nabla Y_{NO}) = \nabla \cdot (\rho \nabla Y_{NO}) + S_{NO} \tag{9}
\]

As discussed in the formation of fuel NOx, fuel NOx mechanisms are more involved. Tracking of intermediate nitrogen-containing species is important. ANSYS FLUENT solves a transport equation for species NO as well as for HCN, NH3 and N2O species:

\[
\frac{\partial (\rho Y_{HCN})}{\partial t} + \nabla \cdot (\rho \nabla Y_{HCN}) = \nabla \cdot (\rho \nabla Y_{HCN}) + S_{HCN} \tag{10}
\]

\[
\frac{\partial (\rho Y_{NH3})}{\partial t} + \nabla \cdot (\rho \nabla Y_{NH3}) = \nabla \cdot (\rho \nabla Y_{NH3}) + S_{NH3} \tag{11}
\]

\[
\frac{\partial (\rho Y_{N2O})}{\partial t} + \nabla \cdot (\rho \nabla Y_{N2O}) = \nabla \cdot (\rho \nabla Y_{N2O}) + S_{N2O} \tag{12}
\]

Where, \(Y_{NH3}, Y_{N2O}, Y_{NO}\) and \(Y_{HCN}\) are mass fraction of NO, N2O, NH3 and HNC in gas mode, and D is the effective diffusion coefficient. Source phrases \(S_{NH3}, S_{N2O}, S_{NO}\) and \(S_{HCN}\) have to be determined in the future for different mechanisms of NOx.
11. The Results of Modeling

11.1 Results without Applying the Field in Three Dimensions

Figure 1. CO₂ comparison between simulation and experimental work, 45 mm away from the nozzle, φ =1, Re = 1500, S = 0

Figure 2. NO comparison between simulation and experimental work, 45 mm away from the nozzle, φ=1.1, Re = 1500, S = 0

11.2 The Results of the Applying Field in Three Dimensions

Figure 3. NOₓ comparison between simulations and experimental work in the bottom of chamber, φ=1.1, Re = 1500, S = 1 and negative polarity
In these diagrams, the Reynolds number and equivalence ratio has been considered 1500 and 1, respectively. Rotation number has been considered constant and equal 1. Working voltages of 0, 1200 and 3000 volts have been provided. As can be seen, by increasing the voltage, the pollution intensity is reduced. Another factor that works in parallel with this is the circulative nature of the current that returns unburned products to the combustion and reaction process.
11.3 Changes in Heat Transfer to the Walls Under the Influence of an Electric Field

As noted, increasing the heat transfer rate due to the electric field, results from the ion wind caused by electric field. This ionic wind causes radial acceleration of the ions. Corona wind makes ions accelerate in the direction of the combustion chamber wall. Ion collisions with neutral molecules makes them accelerate to the wall, too. Therefore, the kinetic energy of all reaction products increasingly raises and after collision with the wall of the combustion chamber transfer their energy, which increases the rate of heat transfer to the walls.

![Graph showing Q/Q0 vs. voltage (v)](image)

Figure 7. comparison between simulation and experimental heat transfer to the walls of the chamber for a different voltage with a positive polarity, $\varphi = 1.1$, Re = 1500, S = 1 and positive polarity

11.4 The Effect of Reynolds Number of the Chamber on Heat Transfer

Reynolds number increases as the flow rate increases. This increased momentum of combustion gases near the chamber walls and thereby increase the heat transfer to the walls. Also, given a constant rotation number, as the Reynolds number increases, tangential velocity increases proportionally. An increase in the tangential velocity causes acceleration and centripetal force and increases the particles moving toward the walls. This also increases the particle collisions to the walls, which further increases the heat transfer to the walls.

11.5 Effect of Electric Field and Equivalence Ratio on Heat Transfer

Enhanced electric field increases the heat transfer to the chamber wall. This is due to the increased radial velocity of the particles and their movement toward the wall in the presence of an electric field with a positive polarity. In the negative polarity, due to the absorption of ions and their trend toward the center electrode a circulating current near the center is generated, concentration in the inlet of the chamber raises and causes an increase in the temperature. Of course, from the entrance to the center of the chamber given the high momentum of the particle, the effect electric power is not perceptible.
Enhanced electric field causes an increase in heat transfer to the walls. This is due to the increased radial velocity at the entrance to the chamber, which increases the particle collisions to the wall.

By increasing the equivalence ratio from 0.7 to 1.1, in addition to that the flame opens, the amount of heat released by the reaction increases. For this reason, heat transfer increases significantly. The highest rate of increase in heat transfer, given with an increase in the equivalence ratio, takes place when the electric field is 3000 volts, that increases heat transfer about 55%.
Figure 10. Changes in heat transfer to the combustion chamber according to various equivalence ratios in the positive polarity, Re = 1500 and S = 1

Figure 11. Changes in heat transfer to the combustion chamber according to various equivalence ratios in positive polarity, Re = 1500 and S = 1

Figure 12. Changes in heat transfer to the combustion chamber according to different voltages in negative polarity, Re = 1500 and S = 1
The highest rate of heat transfer takes place in an electric field with a voltage of 3 kV and equivalence ratio of 1.1. This amount is about 60% the case when the polarity of the electric field is positive. The reason is that in negative polarity, the shape of flame retracts more toward the center. In this case, heat transfer to the walls decreases at the outlet of the chamber. For this reason in total, compared to the positive polarity of the electric field, heat transfer increases at a lower rate.
Figure 15. Changes in the rate of heat transfer to the combustion chamber in terms of various equivalence ratios in negative polarity, \(Re = 1500\) and \(S = 1\)

Figure 16. Comparing heat transfer to the combustion chamber according to various voltages in both positive and negative polarity, \(Re = 1500\) and \(S = 1\) and \(Ψ = 1.1\)

Figure 17. Comparing the heat transfer to the combustion chamber based on different Reynolds numbers, and \(S = 1, \ Ψ = 1.1\)
Figure 18. Comparison of the rate of heat transfer to the combustion chamber according to different Reynolds numbers and $S = 1$, $\Phi = 1.1$

Figure 19. Comparison of the rate of heat transfer to the combustion chamber in terms of different Reynolds numbers and $S = 1$ in both two-dimensional and three-dimensional modes

Figure 20. Comparing total chamber heat transfer to the combustion chamber in terms of different Reynolds numbers, and $S = 1$ in both two-dimensional and three-dimensional modes
Figure 21. Comparison of the rate of heat transfer to the combustion chamber in terms of different voltages, $Re = 1500$ and $S = 1$ in both two-dimensional and three-dimensional modes.

Figure 22. Comparing total heat transfer to the combustion chamber in terms of equivalence ratios, $Re = 1500$ and $S = 1$ in both two-dimensional and three-dimensional modes.

Figure 23. Comparison of the rate of heat transfer to the combustion chamber in terms of different voltages, $Re = 1500$ and $S = 1$ in both two-dimensional and three-dimensional modes.
12. Summary of Results

Considering the explanations provided, it can be concluded that an increase in the voltage and ionic wind increases heat transfer to the walls, which results from a change in velocity and temperature profiles in different sections also increasing the strength of the vortex formed on both sides of the burner and getting close to the center of the flame when the wire has a negative potential difference with respect to the wall. In all velocity and temperature profiles, an increase in voltage does not change the point of maximum velocity and temperature and remains at the center of the combustion chamber. Amplifying an electric field with positive polarity up to 3000 watts increases the heat transfer rate to the wall by 65%. On the other hand, increasing the equivalence ratio is also causing more heat transfer to the walls. But the effect of increasing the electric field on the enhanced heat transfer is much higher compared to the effect of an increase in the equivalence ratio. Rotation makes combustion products return near the area of the input flow. Generating rotatory current using a current rotator also making use of cross-currents and collision currents to generate returned current are two common ways of stabilization of the flame. On the other hand, increasing environmental pollution has increased the efforts to achieve industrial flames with lower emissions. One of these pollutants is nitrogen oxides. Emissions of nitrogen oxide NOx, which is composed of (NO, NO₂, N₂O) contribute to the formation of acid rain, photochemical smog and ozone layer puncture. Reduction of the combustion temperature, reducing the residence time of gases in the flame and preventing the formation of localized spots of high temperature are among the initial actions to reduce nitrogen oxides. In constant voltage and Reynolds equal to 1,000, increasing the equivalence ratio from 0.7 to 1.4 increases increase heat transfer by 45%. In short, in a rotator flame with a constant rotation number, the greatest increase in heat transfer to the walls is caused by an increase in Reynolds number.

After that, the electric field with a positive polarity and then an increase in the equivalence ratio raised heat transfer rate to the walls of chamber. An electric field with positive and negative polarity decreases the flame temperature at the outlet of the chamber. Conversely, an electric field with negative polarity reduces the tangential velocity. Reduction of tangential velocity corresponds to reducing the Coriolis force and thus prevent the opening of the flame. In other words, negative polarity electric field acts against the Rotation.
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