Numerical and Experimental Study of the Arc Fluctuations in a DC Plasma Torch

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Abstract

When the arc voltage fluctuates inside the torch, the velocity and temperature are subject to fluctuation, creating fluctuating temperature and velocity profiles at the torch outlet. This means that the particles experience different conditions, preventing uniform particle acceleration, heating, and melting, that can reduce the coating quality.

Comprehensive three-dimensional unsteady state models of DC argon and argon-hydrogen plasma torches were developed. The arc root attachment point was calculated based on matching experimental voltage fluctuations with arc length estimations from steady state models. Unsteady state results show velocity at torch outlet can fluctuate by up to 30%. The fluctuating velocity and temperature profiles were used to study the plasma jet and particle heating, because a steady state model of a plasma jet cannot predict particle heating. It was demonstrated that the unsteady model could accurately predict both particle temperature and velocity.

The comprehensive simulation model that was built in this research was also used to conduct a new study on a Blue torch, a new design of conventional plasma torches, the plasma gas is composed of argon, carbon dioxide, and methane. The results of these simulations show that shrinking the length of the blue torch results in better torch efficiency. The temperature and
velocity fluctuations at torch outlet is less than the ones observed in conventional torches, due to the nature of plasma mixture, and the longer chamber.

The present study is one of the first research works that studies the effect of arc fluctuations on Turbulence Kinetic Energy (TKE) production. The results show that arc fluctuations, and thus velocity fluctuations at torch outlet, have a considerable effect on TKE.

This study presents a structured framework for modeling the plasma torch. The simulation model is well developed, and produces results that are in good agreement with both electrical and thermal empirical. The results help us get a better understanding of plasma torch, plasma jet stream, and particle heating, which leads to a more clear and accurate image of plasma torch performance.
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Chapter 1
Introduction

1 Introduction

1.1 Introduction to plasma spray coating process

Plasma is the so-called fourth state of matter, and compared to solids, liquids, and gases, it contains the highest energy per unit mass. At room temperature, gases are neutral. As the gas is heated, the collisions between gas molecules become more energetic and may result in dissociation and ionization of the gas molecules. Partially or fully ionized gases are referred to as plasma. The presence of free charged particles, i.e., electrons and ions, makes plasma electrically conductive and strongly responsive to electromagnetic fields. This feature opens the door to a great number of applications. The energy for gas ionization can be supplied by direct current (DC) arc or radio frequency (RF) discharge, or can be provided by high energy photons produced by lasers and/or high electromagnetic fields (e.g., generated by a microwave source). In “thermal plasmas,” the electron temperature is equal to the heavy particle (i.e., molecules, atoms and ions) temperature. One of the most frequently used methods for generating thermal plasma is DC arcs. Due to their high temperatures, thermal plasmas have many interesting applications. Plasma cutting of sheet metals, plasma gasification of organic wastes, plasma metallurgy, and plasma coatings are only a few examples of such applications [1].

Plasma spray technology has been employed widely in industry to apply coatings on different components to protect them from corrosion, wear and heat. The versatile and relatively cost-efficient plasma torches used for spraying applications can be grouped into two types: i) RF inductively-coupled plasma (RF-ICP) torches, and ii) DC plasma torches. In an RF torch, the plasma is generated inductively by passing current through a coil wound around a dielectric tube. The current induces eddy currents within the tube and, once the plasma is ignited, it absorbs power from the coil. RF discharges operate in a controlled atmosphere with a pressure of a few tens of kilopascals [1].
The mechanism of a DC plasma torch relies on the ability of an electric arc to ionization the gas jet stream and produce a plasma jet. The electric current, passing through the torch from the cathode to the anode, partially ionizes the gas inside the torch. Powders are injected into this jet stream of partially ionized gas (i.e., plasma). The plasma jet warms up and accelerates the coating particles during their journey and the resulting mixture of partially ionized gas and hot partially melted particles is then directed at the substrate of the operator’s choice, leaving a uniform thin coating of substance on the substrate [2,3].

On the grounds of the robustness of DC plasma spraying in comparison to radio frequency inductively coupled plasma spraying, DC plasma torches represent more than 90% of industrial thermal plasma torches [4] and for this reason, the focus of this research will be on DC plasma spraying.

To produce a high quality coating, the powder particles should be uniformly heated and accelerated before deposition onto the substrate [5]. In other words, the ability to create a high quality and uniform coating is highly reliant on the torch’s ability to generate a flow of particles with consistent particle temperature and velocity at the point of impact. Assuming that the powder injection is controlled adequately, the consistency of the heating and acceleration of the powders depends to a large extent on the steadiness of the plasma jet. The jet’s steadiness is dictated by the arc fluctuations within the torch. Plasma arcs exhibit strong voltage fluctuations due to movement of the anode arc root attachment. Understanding the arc movement within the torch, and how it affects the flow and temperature fields of the plasma jet exiting the torch, is therefore of great importance [6]. However, analyzing the flow, temperature and electromagnetic fields within a DC plasma torch is extremely challenging, and there are only a limited number of investigations in the literature.

Although new robust tools can measure in-flight particle size, temperature and velocity, there still remains a lack of information about how exactly the arc fluctuates within the torch. Mathematical models can capture some phenomena of arc motion [7]. However, they have not been able to explain all the arc motion instabilities. In this situation, numerical models would be the best tools.

Figure 1-1 shows the SG-100 DC plasma torch used in this research in operation. This torch, manufactured by Praxair, is widely used commercially.
Figure 1-1. The SG-100 DC plasma torch used in this research

Figure 1-2 is a schematic of the cross section of an SG-100 plasma torch. The torch is comprised of two electrodes, i.e., a negatively charged cathode and a positively charged anode, and the water-cooled torch body. Once a voltage is applied between the two electrodes and the plasma is initiated (e.g., by a high frequency tesla coil), an arc is established between the cathode and the anode. For a fixed current, the arc voltage depends on the nature of the plasma gas. Plasma gases may be argon, nitrogen, helium, etc. The arc is continuously heated by joule heating. Electrons are emitted from the cathode by thermionic emission and flow to the anode. Anode root attachment movement is the cause of the arc fluctuations [8].

The gases introduced into the torch are heated by the arc and a plasma jet exits the torch. Powders are injected into the plasma jet where they are then accelerated, heated, and melted (or partially melted) before impacting the substrate, which is placed at some distance from the outlet of the
plasma spray torch [9]. Due to the high plasma temperature, there needs to be an effective way to keep the torch body cool, particularly the anode area. There is a very effective water-cooling system which accomplishes this task [4].

![Schematic of a DC plasma torch showing the locations of the anode and cathode, and the gas flow direction](image)

**Figure 1-2.** Schematic of a DC plasma torch showing the locations of the anode and cathode, and the gas flow direction

### 1.2 Literature review

#### 1.2.1 Background of DC plasma modeling

Developing a complete numerical model of a DC plasma torch capable of predicting of the time-dependent velocity, temperature, and electromagnetic fields is extremely demanding and requires superior computational capabilities. Part of the complexity is related to the existence of large gradients in the flow, temperature and electromagnetic fields, and the fact that the flow is highly turbulent. More importantly, the interaction of the arc with the anode and the arc’s fluctuations are rather complicated and there is no exact model to predict how the movement occurs. The fluctuations, while bounded, are random and dependent on the quality of the anode surface. Early
models in this area assumed laminar two-dimensional steady-state flow regimes. Many researchers (e.g., Westhoff, Szekely) investigated the average and maximum temperatures and velocities inside the torch using two-dimensional laminar flow models of plasma torches [10]. In most of the earlier works, the heat generation (i.e., Joule heating) in the arc, the self-induced magnetic force, and the density of the flow were modeled by solving magneto-hydrodynamics (MHD) equations. It was later discovered that such MHD models need certain corrections to the boundary conditions at the electrodes [11].

Many two-dimensional models have tried to simulate the DC plasma torch [10,12-15]. Amakawa et al. modeled the torch as a two-dimensional symmetrical domain, and conducted a series of numerical simulations to study transferred DC argon plasma. In an improvement to previous work, Amakawa et al. acknowledged the non-equilibrium nature of the system. Therefore, a coupled set of two energy equations - one for electrons, one for gas was solved to find the temperature field inside the domain. The plasma inside the domain was considered to consist of heavy particles (e.g., atoms, ions), and electrons. The calculated temperature of the electrons and gas at each location of the field determined the temperature of the electrons and heavy particles under study [16].

In their study on anode-boundary-layer behavior in a transferred high intensity arc, Amakawa et al. made the following assumptions: that the plasma is laminar, in a steady state, and optically thin. Similar sets of assumptions have been made by several other researchers in this field [10,12-15,17].

Amakawa et al. set up their numerical model to solve the following equations:

i. Continuum momentum equations in r (radial) and z (longitudinal) directions

ii. Two-dimensional magnetic vector potential equation (which is later used to calculate the magnetic field)

iii. Conservation of energy for electrons and heavy particles

iv. Conservation of species

In most research prior to Amakawa et al.’s work, the influences of the flow rate and boundary layer characteristics on the fluid flow were neglected [10,12,13,15]. Amakawa et al. took these interactions into account, and their results show that an increase in the mass flow rate elevates the
temperature and the velocity close to the anode. Amakawa et al. noted that due to pressure effects on the electrons, the density of the electrons close to the anode increases, which results in a drop in the electric potential (aka anode fall) compensating for electron continuity. Moreover, Amakawa et al. showed that increasing the mass flow rate decreases the sheath layer thickness. The heat flux is maximum at the stagnation point, and raising the mass flow rate results in an increase in the heat flux.

Although Amakawa et al.’s research was a major improvement over prior research in this field, there are a few issues that were not addressed. First, the system is modeled as a two-dimensional domain, which fails to capture the three-dimensional phenomena in inherently unstable arc-induced DC recharge domains. Second, there is no mention of the precise size of their computational domain, a parameter critical to every numerical modeling investigation. Third, the outlet boundary condition is modeled as fully developed while in reality there is a longitudinal pressure and velocity gradient at the outlet. Finally, the temperature of the wall along the anode is considered to be constant while in reality the temperature varies along the anode.

As larger computational capability became available, the real features of the plasma jet replaced the aforementioned assumptions [18]. Li and Pfender, for example, studied the steady flow of a plasma jet taking into account the turbulent nature of the jet in their two-dimensional model. Their model, however, only predicted the plasma fields downstream of the anode. Hence, an arc root fluctuation, which is inherently a three-dimensional phenomenon, was not part of this model. Considering the fact that the flow is turbulent in most torch operating conditions, taking the turbulent nature of the plasma jet into account was expected to generate more accurate results. Li and Pfender reported that when turbulence was considered, the predicted temperature profile was in very good agreement with the experimental measurements [19]. It should be emphasized that since the arc within the torch fluctuates and its movements are in three dimensions, two-dimensional models cannot predict temperature and velocity in the arc region.

Over the past decade, a number of attempts have been made to model the three-dimensional behavior of the arc in a DC plasma torch [6,20-24] Results show that the temperature profile predicted by three-dimensional models is much more accurate than that predicted by two-dimensional models. Moreover, the results show that due to an extreme convective effect, the maximum temperature does not occur where the maximum heat is generated [19]. Li et al.
investigated the arc attachment point using Steenbeck’s minimum principle. Considering the fact that Steenbeck’s minimum principle does not consider the unsteadiness of the flow, Li et al.’s results were inaccurate when compared to unsteady state results [25].

1.2.2 Non-equilibrium thermodynamics

One of the most important parameters in developing a numerical model for simulating plasma flow is the series of assumptions that are used to account for the energy transfer and particle interactions within the flow. Under local thermodynamic equilibrium (LTE), all fluid particles (i.e., electrons, ions, neutral molecules and atoms) are assumed to have enough contact and time to transfer and balance energy. In other words, the temperature of light particles (e.g., electrons) and heavy particles (e.g., ions, neutral molecules and atoms) is almost equal. This state of energy balance is generally known as LTE. In many plasmas, however, the interactions between electrons with a high level of energy and heavy particles (atoms/ions) with a low level of energy are much more constrained and uneven. In other words, plasma never experiences absolute LTE because electrons receive energy from the electric field and can only transfer a part of it to the heavy particles through binary collisions. Therefore, simulating a plasma flow considering LTE will only provide an estimation of the state of the plasma inside the torch. Due to the limited availability of capable computational resources, many of the published research works based their DC plasma simulations on the LTE assumption. With recent developments in computational resources, newer models of DC plasma have considered non-LTE effects [26,27].

Amakawa et al. [16] acknowledge that a DC plasma discharge is in fact non-equilibrium. Therefore, a coupled set of two energy equations, one for electrons, one for gas, needs to be solved to find the temperature field inside this domain. The plasma inside this domain is considered to consist of relatively heavy particles (e.g., atoms, ions) and electrons. The calculated temperature of the electrons and gas at each location of the field determines the temperature of the electrons and heavy particles under study [16].

In their study on anode-boundary-layer behavior in a transferred high intensity arc, Amakawa et al. assumed that the gas inside the system consisted of a few species chemically reacting to one
another. Similar sets of assumptions have been made by several other researchers in this field. For example, Trelles et al. assumed that plasma is non-LTE [28-33].

Amakawa et al. set up their numerical model to solve for continuum, momentum equations in \( r \) (radial) and \( z \) (longitudinal) directions, two-dimensional magnetic potential vector equations (used later used to calculate the magnetic field), the conservation of energy for electrons and heavy particles, and the conservation of species.

In most research work prior to Amakawa et al., the influences of flow rate and boundary layer characteristics on the fluid flow were neglected. Amakawa et al. took these interactions into account, and their results show that an increase in the mass flow rate elevates the temperature and velocity close to the anode. Amakawa et al. noted that due to pressure effects on the electrons, the density of the electrons close to the anode increases, which results in a drop in the electric potential (aka anode fall) compensating for electron continuity. Moreover, Amakawa et al. showed that increasing the mass flow rate decreases the sheath layer thickness [16].

Although Amakawa et al.’s research is a major improvement over prior research in this field, their system is modeled as a two-dimensional domain that fails to capture the three-dimensional phenomena in inherently unstable arc-induced DC discharge domains.

The governing equations that explain the non-LTE assumption can be explained as follows. In a DC plasma torch, almost all of the energy in the electric field is absorbed by the electrons through joule heating (\( \sigma E^2 \)) due to their mass. These electrons transfer their excess energy to the heavy particles through elastic and inelastic binary collisions, as shown in Equation 1 (where advection, conduction and radiation are assumed to be negligible) [27]:

\[
\sigma E^2 = \frac{3}{2} k (T_e - T_g) \delta \varnothing_{eg} n_e
\]

where \( \sigma, E, k, T_e, T_g, \delta, \varnothing_{eg}, v_e, \lambda_e, n_e \) are the electrical conductivity of plasma, electric field intensity, Boltzmann’s constant \( (k = 1.3806503 \times 10^{-23} m^2 kg/s^2 K) \), electron temperature, gas (heavy particles) temperature, fraction of transferred energy in an elastic collision, collision frequency \( (\varnothing_{eg} = v_e/\lambda_e) \), electron speed, electron mean free path, and electron number density, respectively. \( \delta \) is equal to \( \frac{2m_e}{m_g} \), where \( m_e \) and \( m_g \) are the masses of the electrons and gas (heavy
particles), respectively. In addition, the following expressions can be used to calculate the electrical conductivity and mean free path of electrons for monatomic plasma:

$$\sigma = e^2 \lambda_e n_e / v_e m_e$$  \hspace{1cm} 1-2$$

and

$$\lambda_e = \left[ \sum_j n_j Q_{ej} \right]^{-1}$$  \hspace{1cm} 1-3$$

where $n_j$ is the number density of the heavy particles and $Q_{ej}$ is the collision cross section between an electron and species $j$ [1]. Putting together all of the aforementioned equations, the energy exchange rate can be expressed as [27,34]

$$E_{eg} = \frac{3}{2} k (m_e/m_g) \theta_{eg} n_e (T_e - T_g)$$  \hspace{1cm} 1-4$$

where $E_{eg}$ is the transferred energy between electrons and gas. Considering that this energy is provided by the electric field [1], we have:

$$\frac{T_e - T_g}{T_e} = \frac{3\pi}{32} \frac{\lambda_e e E^2 m_e}{\frac{3}{2} kT_e m_g}$$  \hspace{1cm} 1-5$$

Using Equation 1-5, we can find the relation between the electron temperature and the gas (heavy particle) temperature. The term in the bracket is the ratio of the energy gained by the electrons in the electric field to the average kinetic energy of the thermal motion. This equation shows that low pressure and/or a high strength of electric field intensity prevents the establishment of equilibrium [1]. Therefore, in low pressure plasma, and close to the cathode and anode in DC plasma, the equilibrium condition is not satisfied. The other regions of the flow, however, can be considered to be close to LTE. Non-LTE models predict more accurate results for regions close to the electrodes. However, these models are computationally expensive and complex [31]. Recently, a new improved LTE model has been suggested. The non-equilibrium state may occur close to the two electrodes as at those locations the heavy atom/ion temperature is relatively low but the electric field intensity is high. In this model, the electron temperature can be extracted from tables based on temperature, and the strength of the electric field (and hence electric conductivity) can be
calculated based on the electron temperature. However, these improved LTE models fail to capture the attachment point [35]. It should be mentioned that due to the very high temperatures, radiation plays an important role in the energy balance. In this study, we can consider radiation as a net emission term instead of solving very complex integral-differential equations [36].

1.2.3 Arc fluctuations

Arc dynamics play the most important role in plasma jet dynamics. There are three forces that act on the arc in a DC plasma torch: the drag force, the Lorentz force, and the plasma gas dynamics thrust [6,32]. Lorentz force acts on the arc because the arc is an electrical current and the force is generated due to a self-induced magnetic field. The drag force is the force acting on the arc column due to the high speed of the gas. The plasma gas dynamic thrust is a momentum related force generated by the discharge of the arc on the magnetic wall. A dynamic equilibrium is obtained by the interaction between these three forces.

Up until 2006, numerical models of DC plasma torches were generally built based on the principle that the arc is operating under steady-state conditions. Measurements of the arc voltage showed that the voltage strongly fluctuates while the arc current remains constant. The voltage fluctuations are due to movements of the arc root (on the anode) which change the length of the arc and, hence, its voltage. The jumps are due to the imbalance between the drag force experienced by the arc and the Lorentz force, which results in fluctuations of the net angular momentum. The interactions of the drag and Lorentz forces, therefore, became known as the most important parameter in arc dynamics [6,32].

One of the most elaborate investigations into the reattachment process was conducted by Trelles et. al. [6,22,30-32]. Trelles et al. employed LTE and non-LTE models in their numerical model and studied reattachment of the arc in DC plasma. Using a Finite Element Model (FEM) based solver, they developed a very small domain for a three-dimensional model of a DC plasma arc (with maximum 65000 nodes). However, due to the low efficiency of the FEM in fluid systems, the balances of conservation quantities are not satisfied. In Trelles et al.’s studies, the LTE model was applied to the aforementioned domain to create artificial electrical conductivity close to the anode to ensure the flow of electrical current to the anode. Moreover, for the arc breakdown and
repositioning, they considered a virtual breakdown model that simplifies the computation but fails to capture some details of the phenomena. In spite of the detailed study conducted by Trelles et. al. on the arc root attachment point, the instability of the arc and the effects of that instability were not fully studied.

Several researchers have investigated the voltage fluctuations in DC plasma torches [8,22,30,37]. According to these publications, there are three modes of voltage oscillations that can be observed:

Restrike fluctuation mode: This is characterized by a large average and large voltage fluctuations with a saw tooth shape profile, as shown in Figure 1-3. Restrike oscillations show intermittent behavior. This fluctuation mode occurs when the electric current is low and the mass flow is high (e.g., electric current less than 400A and a mass flow rate of more than 70slpm for Ar). Also, an eroded anode can reduce the jumps in the arc root attachment point (as illustrated in Figure 1-4) and cause a large increase in voltage and, thus, restrike mode behavior [8,37].

Takeover fluctuation mode: This is characterized by a small average and small voltage fluctuation with a sinusoidal shape profile, as shown in Figure 1-3. By increasing the electric current and decreasing the mass flow rate, the average voltage reduces and the wave shows almost sinusoidal characteristics with low amplitude. Coating analysis shows that operating at takeover mode provides enough fluctuation for the uniform heating of the gas jet stream and particles and, thus, produces the best coating quality. Regular DC plasma torches do not operate at this range of electric current and mass flow rate.

Steady mode: which is characterized by a small average and almost zero voltage fluctuations, as shown in Figure 1-3. When the electric current increases dramatically (e.g., 1000A), the voltage will experience steady mode [8]. Under this operating condition, the voltage decreases dramatically and the thermal efficiency drops.

The use of thermal spray coating has not been fully integrated into the industrial production chain yet because it is still hard to control coating quality [8,30,38]. Particle properties and the microstructure of the coating can be affected by small changes in operating conditions, and the instability and low reproducibility brings along concerns for industrial applications considering this technology [38]. In the present research, an attempt is made to understand these issues by
presenting a comprehensive study of DC plasma torch operation and the parameters that affect their operating conditions.

Several researchers (e.g., Selven et al., Ramachnan et al., Wang et al.)\cite{39,40} have proposed that the best approach for finding the arc root attachment point is to solve the steady state model several times, each with a different arc root attachment point (different lengths and radii) and select the point which represents the best results (i.e., results that best match experimental measurements). In the present thesis, this approach was adopted to build the initial condition of the unsteady model. In addition, the research presented in the literature offered a few opportunities for continued development. First, the simulations were based on steady state models. Second, Lorentz force was not contemplated in their simulation models.
In most research work in this field from 2006 through 2015 [6,24,28,31-33,41,42], authors have made several assumptions when simulating arc breakdowns and arc movements in an electrical field. For example, some researchers applied a defined maximum electric field strength constraint to determine when the arc should break down. In more recent papers (e.g., Trelles[29]), however, researchers noted that they made no additional assumptions for arc root unsteady state detachment, and stated that the arc movement were due to a residual computational error. He mentions that these arc movements depended on the number of nodes and spatial discretization. In other words, arc root attachment results are mesh dependent, a characteristic that makes simulation results debatable. Results from Trelles’s work show that the maximum velocity and temperature are merely functions of the electric current matching similar findings from experiments [29,33].

Studying the mesh organization in Trelles’s work [31], it appears that the number of mesh nodes in azimuthal direction is relatively small, which may lead to a failure to capture arc root attachments accurately. Trelles used FEM in discretizing the governing equations in the proposed unsteady three-dimensional CFD model of non-transferred DC argon plasma. Although FEM is a well-accepted method for use in problems of a similar nature, there are debates that this may not be the best method for plasma torch simulation. For example, FEM has repeatedly been found to produce less accurate results compared to FVM [43]. Moreover, Trelles did not report the thermal efficiency of their system, an important parameter that is critical to validating research work in
this field. Since the main purpose of a plasma torch is to heat particles uniformly, all simulation results need to show that the thermal efficiency calculated from the simulation results matches the thermal efficiency found from experiments, otherwise the model is not thermally matched with the experimental results [31].

In 2015, Alaya et al. published a paper in which they discuss the results of their incompressible laminar LTE model. Alaya et al. included the solid body of the cathode in their simulation domain. Therefore, there is no need to use standard Gaussian profiles for the electric current at the cathode tip. This approach is valued for its inclusivity and the sensible temperature and electric current profiles produced from the results. However, it is computationally expensive because the system consists of a solid and a fluid domain with dramatically different properties [44]. Prior to this, Rao and Munz experimentally investigated the effects of the cathode microstructure on the erosion of the cathode and plasma jet. Results show the cathode surface characteristics can change the plasma jet velocity and cathode erosion rate [45].

1.2.4 Plasma jet and particle injection

To produce a high quality coating, powder particles should be uniformly heated, melted, accelerated, and deposited onto the substrate [5]. In other words, the ability to create a high quality and uniform coating is strongly reliant on the torch’s ability to generate a flow of particles with consistent particle temperature and velocity at the point of impact [46,47]. Assuming that the powder injection is controlled adequately, the consistency of the heating and acceleration of powders is dependent on the steadiness of the plasma jet. This is dictated by the arc fluctuations within the torch [48]. Plasma arcs exhibit strong voltage fluctuations which are due to the movement of the anode arc root attachment. It is, therefore, of great importance to understand the arc movement within the torch and how it affects the flow and temperature fields of the plasma jet exiting the torch [6]. Understanding the flow, temperature and electromagnetic fields within the DC plasma torch is extremely challenging and there are only a limited number of investigations in the literature from which to draw [49].

Although new robust tools can measure in-flight particle size, temperature and velocity, there is still a lack of information about how exactly the arc fluctuates within the torch [50,51].
Mathematical models can explain some phenomena which happen in arc motion [7]. However, they have not been able to capture all instability in the arc motion. In this situation, numerical models are the best tools to use [52-56].

Lee’s work was the first comprehensive numerical modeling of plasma jet and particle injection proposed [53,54,57]. Those simulations included coating particles, however, the problem was modeled as a steady state fluid flow. Moreover, their models did not include the torch [48].

Trelles conducted a similar series of simulations in his research on plasma jet flow in a non-transferred arc plasma torch impacting on a flat substrate [58-60]. Trelles modeled the DC argon plasma torch as an FEM three-dimensional non-LTE model. The model included an assumption that significantly improved the results because it better reflected the fact that the non-equilibrium condition of a plasma jet affects the heat transfer to the substrate and, thus, the temperature distribution and coating uniformity over the substrate. Trelles made the assumption that the fluid flow is laminar. This assumption simplifies the problem and brings down the computational cost, however, it leads to a failure to capture the true nature of the flow. Moreover, the outlet discharge was assumed to be of the same mixture of plasma inside the torch. In other words, it was assumed that the plasma jet discharged into plasma gas, argon.

When coating particles are injected (sprayed) into a plasma jet stream, plasma jet heats and melts the solid particles. For some materials, the particle may experience evaporation [55,56,61]. At the same time, as they are heated, the particles are accelerated through the plasma jet stream and are guided through the torch and dispatched from the torch at the outlet. Considering the fact that the instability of the arc inside the torch is the main source of plasma jet stream characteristics, it is fair to say that by studying the correlation between the plasma jet stream and heating, acceleration and trajectory of coating particles, we are actually investigating the correlation between arc instability and the aforementioned characteristics of coating particles [47,62].

1.2.5 Objectives

As discussed previously, to produce a high quality coating, powder particles should be uniformly heated, accelerated, and deposited onto the substrate [5] and this is contingent upon the torch’s ability to generate a flow of particles with consistent particle temperature and velocity at the point
of impact. Assuming that the powder injection is controlled adequately, the consistency of heating and acceleration of powders, to a large degree, depends on the steadiness of the plasma jet. This is dictated by the arc fluctuations within the torch. Plasma arc exhibits strong voltage fluctuations which are due to the movement of the anode arc root attachment. Understanding the arc movement within the torch and how it affects the flow and temperature fields of the plasma jet exiting the torch is therefore of great importance [6].

Although new robust tools can measure in-flight particle size, temperature and velocity, still there is lack of information about how exactly the arc is fluctuating within the torch. Mathematical models can explain some phenomena which happen in arc motion [7]. However, they have not been able to capture all instability in arc motion. In this situation, numerical models are the best tool.

The objective of the present research is to develop a three-dimensional numerical model of the flow, temperature, and electromagnetic fields within a DC plasma torch and investigate the effects of arc instability on the properties of the plasma jet which exits the torch including how these instabilities affect particle heating injected downstream of the anode.

In this research, a comprehensive three-dimensional numerical simulation of a plasma jet inside a DC plasma torch will be created, based on investigations of arc instability parameters, flow properties, and torch efficiency. Heat transfer in the torch will also be studied with the intention of creating a base for future works on online and offline controlling of the arc instability for the main and ultimate goal of creating an ideal uniform ultimate quality coating. The steps of this research are as follows:

**Step 1: Modelling of DC plasma torch;**

An inclusive three-dimensional numerical model of a DC plasma torch will help to simulate the electric potential and magnetic vector fields accurately, and predict a precise value for the Lorentz force and Joule heating.

**Step 2: Implementing non-LTE methodology into the model;**

By implementing non-LTE into our model, the simulation of close to anode will be more accurate. In the non-LTE model, the electron temperature is different from the gas
temperature. Therefore, the electron temperature should be calculated first. A new non-LTE method was used [35]. However, ELT and non-LTE results were similar. So, LTE assumption in a DC plasma is valid.

**Step 3: Introducing unsteady conditions of the flow into modelling;**

As the flow is intrinsically unsteady, an unsteady model should be implemented to see all processes in the torch. Movement of the arc can be seen in an unsteady model. However, it is computationally costly to solve this problem with the unsteady model due to the large number of equations and numerically large domain.

**Step 4: Studying the arc root attachment point;**

Predicting the arc root attachment point is important for two main reasons: (i) the main erosion occurs at the attachment point, making this point of the torch vulnerable to early thermal fatigue, failure, or meltdown, (ii) the consistency of the root attachment point helps maintain uniform flow and hence consistent and high quality coating.

**Step 5: Experimental study of voltage fluctuations;**

A number of experiments will be conducted on an SG-100 torch to find the overall operation conditions of the torch, including the average voltage drop and inlet and outlet cooling water temperatures and efficiencies of the torch for different mass flow inlet and electric currents. During each experiment, the voltage fluctuations will be measured using an oscilloscope. These voltage fluctuations will then be analyzed to capture the form of the arc. The data will also be processed by a Fast Fourier Transform tool to find the dominant frequency for each state and compare it with numerical results.

**Step 6: Modeling the interaction of the plasma jet stream with the injected particles;**

At this step, the particle heating, melting and accelerating will be studied and the effects of arc fluctuations on particle heating will be investigated.

**Step 7: Using the constructed model to evaluate the Blue Torch [63] operation and design;**
At this step (particle heating), the Blue Torch designed by Center for Advanced Coting Technologies (CACT) will be evaluated with the model.

Step 8: Study the new plasma mixtures

A new set of simulations was developed to study the plasma jet stream composed of Ar and H$_2$ in SG100 torch. Furthermore, another series of simulations were run to model a jet stream composed of CO$_2$, CH$_4$, and Ar inside a blue torch.

Step 9: Study of the effects of different turbulence models on the torch results;

Most of the numerical models in the plasma torch modeling field have used the standard $k - \varepsilon$ turbulence model [64].
2 Governing equations

This study involved the consideration of three components: conditions inside the torch, the plasma jet, and the particle injection.

2.1 Flow inside the torch

Assumptions:

- Continuum assumption is valid
- Plasma is ideal gas
- Net emission coefficient is used to model radiation
- Viscous dissipation is negligible
- Gravitational effect is negligible
- Turbulent flow

Figure 2-1 shows schematics of SG-100 torch [65].

Assuming LTE, the conservation equations for mass, momentum and energy used in this study are described below.

Continuity:

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0 \]  \hspace{1cm} 2-1

Momentum:

\[ \rho \left( \frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \nabla \vec{V} \right) = -\nabla \left( p + \frac{2}{3} \mu_{eff} \vec{V} \cdot \nabla \vec{V} \right) + 2\nabla \cdot \left( \mu_{eff} \vec{S} \right) + \vec{j} \times \vec{B} \]  \hspace{1cm} 2-2

Energy:
\[
\rho c_p \left( \frac{\partial T}{\partial t} + \vec{V} \cdot \nabla T \right) = \nabla \cdot \left( \kappa_{eff} \nabla T \right) + \frac{DP}{Dt} - \dot{R} + \frac{j^2}{\sigma}
\]

where \( \rho, \vec{V}, \mu_{eff}, j, \vec{B}, c_p, T, \kappa_{eff}, \dot{R}, P, \vec{S} \) are the density, velocity, effective viscosity, electric current density, magnetic field, specific heat, temperature, effective thermal conductivity, volumetric radiative loss, pressure, and shear stress tensor, respectively.

Figure 2-1. SG-100 torch geometry

Simulating a case of fluid flow with computational fluid dynamics (CFD) generally requires solving Navier–Stokes partial differential equations (PDE), namely conservation of momentum,
and conservation of mass (continuity) in all main coordination directions x, y, z. In order to find temperature changes across the fluid flow, enthalpy (energy) equations are added to these sets of PDEs and solved over each node. If the fluid flow is a turbulent fluid flow, a turbulent model must be selected and coupled into the PDEs.

Navier-Stokes PDEs are a set of equation systems that describe the motion of a viscous fluid. These equations are of the form described in equation 9 [66,67]:

\[
\frac{\partial}{\partial t}(\rho \Phi) + \text{div}(\rho u \Phi) = \text{div}(\Gamma \text{grad} \Phi) + S_\Phi \tag{2-4}
\]

where \( \Phi \) is a conservative parameter. The first term (transient term) of the above equation shows the changes of parameter \( \Phi \) with time. This term is zero in a steady flow. The second term of this equation represents the motion of fluid (of velocity \( u \)). \( \text{div}(\Gamma \text{grad} \Phi) \) represents the fluid transfer due to diffusion (both molecular diffusion and turbulent diffusion) and \( \Gamma \) is the effective diffusion coefficient. The source term \( S_\Phi \) represents the generation or degeneration of parameter \( \Phi \). For example, when the conservative variable \( \Phi \) is enthalpy, \( S_\Phi \) could be a source of thermal energy in the system.

In a turbulent fluid flow, the viscosity (\( \mu \)) needs to be replaced by the effective turbulent viscosity (\( \mu_t \)), which is a function of the fluid flow velocity. The dependency of \( \mu_t \) to velocity is defined differently in every turbulent model. In each of these models, \( \mu_t \) is calculated using a set of equations that relate the kinetic energy of the turbulent flow to the rate of kinetic energy dissipation [66].

In the \( k - \varepsilon \) turbulent model, the kinetic energy of the fluid flow (\( k \)) is correlated to the rate of kinetic energy dissipation in the fluid flow (\( \varepsilon \)). In this model, we assume that the fluid flow is fully turbulent and that the molecular viscosity effects are negligible.

The following transfer equations describe how the kinetic energy of the fluid flow (\( k \)) is correlated to the rate of kinetic energy dissipation in the fluid flow (\( \varepsilon \)).

\[
\frac{D(\rho k)}{Dt} = \frac{\partial}{\partial x_i} \left[ \mu_t \frac{\partial k}{\partial x_i} \right] + G_k + B - \rho \varepsilon \tag{2-5}
\]
\[ \frac{D(\rho \varepsilon)}{\partial t} = \frac{\partial }{\partial x_i} \left[ \mu_t \frac{\partial \varepsilon}{\partial x_i} \right] + C_{1\varepsilon} G_k \frac{\varepsilon}{k} + C_{1\varepsilon}(1 - C_3) \frac{\varepsilon}{k} B - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \]  \hspace{1cm} 2-6

\[ \mu_t = C_\mu \frac{k^2}{\varepsilon} \]  \hspace{1cm} 2-7

where \( G_k \) represents the turbulent kinetic energy generation due to gradients of average velocity. \( B \) represents the effects of buoyancy forces and is calculated as explained below. \( C_\mu = 0.09, C_{1\varepsilon} = 1.44, \) and \( C_{2\varepsilon} = 1.92 \) are constants. \( \sigma_k = 1.0 \) and \( \sigma_\varepsilon = 1.3 \) represent turbulent Prandtl numbers for \( k \) and \( \varepsilon \), respectively [68-70].

To predict the magnetic and electric fields, it is necessary to solve the electric potential, \( \Phi \), and magnetic vector potential fields, \( \vec{A} \), in three dimensions. The electromagnetic equations of the flow under study are described below [1-3, 27]:

\[ \nabla \cdot (\sigma \nabla \Phi) = 0 \]  \hspace{1cm} 2-8

\[ \nabla^2 \vec{A} = -\mu_0 \vec{j} \]  \hspace{1cm} 2-9

In this study, the electric potential and magnetic vector potential (Equations 2-8 and 2-9), in addition to the energy and momentum equations, were solved. Then, using Equations 2-10 and 2-11 the electrical field, current density and magnetic field can be calculated. Finally, the source terms in the momentum and energy equations (i.e., Lorentz force and Joule heating) were found.

\[ \vec{E} = -\nabla \Phi - \frac{\partial \vec{A}}{\partial t} \]  \hspace{1cm} 2-10

\[ \vec{B} = \nabla \times \vec{A} \]  \hspace{1cm} 2-11

\[ \vec{j} = \sigma (\vec{E} + \nabla \times \vec{B}) \]  \hspace{1cm} 2-12
where $\phi, \sigma, \vec{A}, \mu_0, \vec{E}$ and $\vec{B}$ are the electric potential, electrical conductivity, magnetic vector potential, permeability of free space, electric field intensity and magnetic field, respectively. $\vec{j} \times \vec{B}$ is the Lorentz force, and $J^2/\sigma$ is the Joule heating term.

The SG-100 torch, was selected as the subject for the computational models and as the test stand. The model will be used to evaluate the Blue torch in a subsequent section.

The SG-100 plasma torch schematic and mesh are shown in Figure 2-1 and Figure 2-2 respectively, and the Blue torch is shown in Figure 2-3 [71].

In the simulated model, as outlined in Chapter 4, plasma is considered as a continuum and radiation is modeled with net emission coefficient [44]. To turbulence model, a $k-\epsilon$ standard turbulence model is used in this stage [29,33]. A non-local thermodynamics equilibrium model based on Huang et al was considered, however, the results did not differ meaningfully from the results that included a sheath layer. Therefore, the plasma is considered to be in a local thermodynamics equilibrium (LTE) state with a very thin sheath layer (1 mm) [44].

A three-dimensional model of an SG-100 [35] non-transferred DC argon and argon-hydrogen mixture plasma torch was created with 800,000 cells. Generating a code to implement the relations required to solve the electric potential and magnetic vector potential equations in commercial software, FLUENT. The equations were solved for a range of arc lengths and radii within the torch. Boundary conditions were set as mentioned in Table 2-1.

<table>
<thead>
<tr>
<th>Table 2-1. Boundary conditions</th>
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<tbody>
<tr>
<td><strong>Inlet</strong></td>
</tr>
<tr>
<td>$P$</td>
</tr>
<tr>
<td>$\vec{V}$</td>
</tr>
<tr>
<td>$T$</td>
</tr>
<tr>
<td>$\phi$</td>
</tr>
<tr>
<td>$\vec{A}$</td>
</tr>
</tbody>
</table>
Figure 2-2. SG-100 mesh
For the electric current and temperature boundary conditions on the cathode, Equations 18 and 19 are used, respectively [6].

\[ j(r) = j_0 \exp\left(-\left(\frac{r}{r_c}\right)^4\right) \]
\[ T(r) = 300 + 3200 \exp[-\left(\frac{r}{2r_c}\right)^4] \]

For the thermal boundary conditions at the anode, convection heat transfer \( (h=100000 \text{ W/Km}^2, T_w = 300 \text{K}) \) is implemented and \( r_c \) in Equations 2-13 and 2-14 is assumed to be 0.913 mm [6].

The properties for argon, argon-hydrogen, and \( \text{CO}_2 \)-based mixtures were taken from different sources [1,3,36,72-74].

![Figure 2-4. Blue torch size](image)

### 2.2 Plasma jet stream at torch outlet

As explained in the introduction to this thesis, generating a uniform coat on a substrate using a plasma torch requires a uniform plasma jet stream. It is important to have a clear picture of the phenomena occurring inside the torch and their effects on the plasma jet stream. It is also important
to look at this problem from another point of view. That is the effect of the plasma jet stream characteristics on the particles.

In order to achieve a good grasp of the particle characteristics, we need to add yet another zone to our CFD simulation. This new zone is the domain that surrounds the torch outlet and includes the substrate.

The outlet plasma jet is the discharge of hot gas (argon in this study) shooting out of the torch into the atmosphere (air in this study). This outlet plasma jet is subject to two different environments: i-, the domain inside the torch that defines the characteristics of the outlet plasma jet before it enters the atmosphere; and ii-, the domain outside the torch which directly affects the characteristics of the outlet plasma jet and changes the flow. In other words, there are two kind of instabilities related to gas discharge, I) the instability that comes from arc fluctuations inside the torch and II) the instabilities from the shear layer between the hot and cold gas outside of the torch.

The atmosphere surrounding the torch is air. In several previous studies [29, 58, 60], the researchers assumed that the outlet plasma discharged into a gas the same as the gas inside a torch. This assumption simplified the simulations. Furthermore, incorporating different materials in different zones of simulation posed computational costs which were considered too high. However, it is the author’s belief that the aforementioned assumption will not result in a realistic simulation. Therefore, in the present study, the ambient gas is considered to be air. The two main components of air are nitrogen (79%) and oxygen (21%). A model was created in FLUENT.

In addition, a set of assumptions needs to be determined for simulating the outlet plasma jet stream and the domain surrounding it. These assumptions are listed below and explained further in the following paragraphs of this chapter.

- The flow is unsteady and the inlet velocity and temperature profile are unsteady and they are taken from the torch results
- Continuum assumption is valid
- Plasma is considered an ideal gas
- The plasma gas (argon, argon-hydrogen or CO2 mixture) discharges into ambient air
- Radiation loss is considered (net emission coefficient)
• Viscous dissipation and pressure work is negligible
• Gravitational effect is considered
• Turbulent flow
• Gravity is considered

In simulating the outlet plasma jet stream, the following energy, momentum, mass species, and turbulence equations are solved for the external region.

Continuity:
\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \quad \text{2-15} \]

Momentum:
\[ \rho \left( \frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = -\nabla (P + \frac{2}{3} \mu_{eff} \mathbf{V} \cdot \mathbf{V}) + 2\nabla \cdot (\mu_{eff} \overline{\mathbf{S}}) + \overline{\mathbf{S}_p} + \mathbf{g} \quad \text{2-16} \]

Energy:
\[ \rho c_p \left( \frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T \right) = \nabla \cdot (\kappa_{eff} \nabla T) - \hat{R} + \hat{Q}_p \quad \text{2-17} \]

where \( \rho, \mathbf{V}, \mu_{eff}, c_p, T, \kappa_{eff}, \hat{R}, P, \overline{\mathbf{S}}, \overline{\mathbf{S}_p}, \mathbf{g}, \) and \( \hat{Q}_p \) are the density, velocity, effective viscosity, specific heat, temperature, effective thermal conductivity, respectively, and \( \hat{R}, P, \overline{\mathbf{S}}, \overline{\mathbf{S}_p}, \mathbf{g}, \) and \( \hat{Q}_p \) are the volumetric radiative loss, pressure, and shear stress tensor, momentum equation source term from particles, gravity, and energy source term from particles, respectively.

To solve the conservation equations for the chemical species in the jet discharge, the local mass fraction of each species, \( Y_i \), should be calculated from the transport equation of that species. The conservation equation takes the following general equation:

\[ \frac{\partial (\rho Y_i)}{\partial t} + \nabla \cdot (\rho \mathbf{V} Y_i) + \mathbf{V} \cdot \mathbf{j}_i - R_i - S_i = 0 \quad \text{2-18} \]
where $J_i$ is the diffusion of species $i$, $R_i$ is the rate of production of species $i$ by chemical reaction and $S_i$ is the rate of production from any source, which is zero here. Oxygen, nitrogen and plasma mixture are species for this simulation.

2.3 Particle injection

As explained before, when the plasma jet stream is generated inside the torch, the coating material is sprayed into the plasma jet stream. The plasma jet stream heats and accelerates the particles and guides them towards the substrate. In order to study the conditions of these particles throughout their journey, we need to add particle injection to our simulation set up. A set of assumptions need to be placed for adding this concept into simulations. These assumptions are listed below and explained further in the following paragraphs of this chapter.

Assumptions:

- Particles are spherical
- Biot number is very low, therefore, lumped heat capacitance approach is valid
- Particle-particle interactions are neglected. This is a logical assumption for plasma spray particle mass flow rate
- Turbulent dispersion of particles is considered.
- Virtual mass force, which is the force required to accelerate the fluid surrounding the particle, is neglected
- Thermophoretic force is neglected
- Brownian force is neglected
- Saffman’s lift force is neglected
- The force due to pressure gradient is neglected because the gas density is much smaller than the density of particles
- Nickel is considered as the powder material
- No evaporation of powder is considered [75]
- Radiative heat transfer is considered
2.3.1 Particle heating and motion

For particle trajectory, the discrete phase model (DPM) was used. This model uses the Lagrangian reference method to calculate particle forces and heat transfer. For each particle, the inertia, drag force and gravity force are:

\[
\frac{d\vec{u}_p}{dt} = F_D(\vec{u} - \vec{u}_p) + \frac{\vec{g}(\rho_p - \rho)}{\rho_p} + \vec{F}
\]

2-19

\[
F_D = \frac{18\mu C_D Re}{\rho_p d_p^2} \frac{C_D}{24}
\]

2-20

where \(\vec{F}\) is any source term force per unit particle mass (e.g., virtual mass force). Virtual mass force is the force required to accelerate the fluid surrounding and adjacent to each particle. \(F_D(\vec{u} - \vec{u}_p)\) is the drag force per unit particle mass. \(\vec{u}\) is the fluid velocity, \(\vec{u}_p\) is the particle velocity. \(\mu\) and \(\rho\) are the viscosity and density of the fluid, respectively. \(\rho_p\) is the particle density and \(d_p\) is the particle diameter.

We can define the relative Reynolds number for the particles \(0.1 < Ma_p < 2\) and \(0.2 < Re < 10^4\). These ranges are sufficient for the applications in this research.

\[
Re_p = \frac{\rho D_p |\vec{u} - \vec{u}_p|}{\mu}
\]

2-21

The drag force is extracted from the correlation proposed by Crowe [76,77]. The drag coefficient has been used in this study, is given in Table 2-2.

The heat transfer from the plasma flow to the particles is:

\[
m_p c_p \frac{dT_p}{dt} = h A_p c_p (T_\infty - T_p) + \epsilon_p A_p \sigma (T_w^4 - T_p^4) + Q_{Melting} + Q_{Evaporation}
\]

2-22

where \(m_p, c_p, T_p, A_p, T_\infty, T_w, \epsilon_p, \sigma, Q_{Melting}\), and \(Q_{Evaporation}\) are the mass of particle, specific heat, particle temperature, particle surface, plasma temperature, wall temperature, particle surface area, particle emissivity, Stefan-Boltzmann constant, latent heat and evaporation heat,
respectively. The heat transfer is calculated without considering evaporation in the current numerical simulation because evaporation is very small for nickel particles.

Table 2-2. Drag coefficients

<table>
<thead>
<tr>
<th>Range</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Re &lt; 0.01$</td>
<td>$C_D = \frac{24}{Re}$</td>
</tr>
<tr>
<td>$0.01 &lt; Re &lt; 20$</td>
<td>$C_D = \frac{24}{Re} [1 + 0.1315 Re^{0.82-0.05w}]$</td>
</tr>
<tr>
<td>$20 &lt; Re \leq 260$</td>
<td>$C_D = \frac{24}{Re} [1 + 0.1935 Re^{0.6305}]$</td>
</tr>
<tr>
<td>$260 &lt; Re \leq 1500$</td>
<td>$\log_{10} C_D = 1.6435 - 1.1242w + 0.1558w^2$</td>
</tr>
<tr>
<td>$1500 &lt; Re \leq 1.2 \times 10^4$</td>
<td>$\log_{10} C_D = -2.4571 + 2.5558w - 0.9295w^2 + 0.1049w^3$</td>
</tr>
<tr>
<td>$1.2 \times 10^4 &lt; Re \leq 4.4 \times 10^4$</td>
<td>$\log_{10} C_D = -1.9181 + 0.6370w - 0.0636w^2$</td>
</tr>
<tr>
<td>$4.4 \times 10^4 &lt; Re \leq 3.38 \times 10^5$</td>
<td>$\log_{10} C_D = -4.3390 + 1.5809w - 0.1546w^2$</td>
</tr>
<tr>
<td>$3.38 \times 10^5 &lt; Re \leq 4 \times 10^6$</td>
<td>$C_D = 29.78 - 5.3w$</td>
</tr>
<tr>
<td>$4 \times 10^5 &lt; Re \leq 10^6$</td>
<td>$C_D = 0.1w - 0.49$</td>
</tr>
<tr>
<td>$10^6 &lt; Re$</td>
<td>$C_D = 0.19 - \frac{8 \times 10^4}{Re}$</td>
</tr>
</tbody>
</table>

$w = \log_{10} Re$

The convective heat transfer coefficient is extracted from Witaker equation [78]:

$$Nu_p = 2.0 + \left[ 0.4 Re_p \frac{1}{2} + 0.06 Re_p \frac{3}{2} \right] Pr^{0.4} \left( \frac{\mu_{\infty}}{\mu_s} \right)^{\frac{1}{4}}$$

where $Nu_p$, and $Pr$ are Nusselt numbers ($Nu_p = \frac{hD}{k}$) and Prandtl numbers. $Re_p$, $\mu_{\infty}$, $\mu_s$ are Reynolds number of particle, viscosity of gas in the plasma flow temperature, and viscosity of gas in the particle temperature, respectively.
To calculate the trajectory particle heat transfer, the lumped heat capacity assumption is used. This assumption is valid when the particle temperature is uniform. When the Biot number is less than 0.1, the lumped heat capacity assumption is valid. The Biot number is defined as:

\[ \text{Bi} = \frac{h L_c}{k} \]  \hspace{1cm} (2-24)

where \( h, L_c, \) and \( k \) are, respectively, the convective heat transfer coefficient of particle, characteristic length \( L_c = \frac{V}{A} \) (\( V \) is particle volume and \( A \) is particle surface area), and particle heat conductivity.

\[ k = 92 \frac{W}{Km} \]  \hspace{1cm} (2-25)

\[ L_c = \frac{D}{6} = \frac{90}{6} = 15 \mu m \]  \hspace{1cm} (2-26)

To calculate the convective heat transfer coefficient the simple equation from Witaker is used to calculate the Nusselt number [78]:

\[ Nu_p = 2.0 + [0.4Re_p^{\frac{1}{2}} + 0.06Re_p^{\frac{2}{3}}] Pr^{0.4} \left( \frac{\mu_\infty}{\mu_s} \right)^{-\frac{1}{4}} \]  \hspace{1cm} (2-27)

The worst case scenario was considered when calculating the Biot number. The largest particle used in this study was considered. The particle diameter is 90 \( \mu m \). The average Reynolds number is almost 50. Thus, we can calculate the \( Nu \) and \( Bi \) numbers.

\[ Nu = 7.13 \rightarrow h = \frac{kNu}{D} \rightarrow Bi = 0.0098 \ll 0.1 \]  \hspace{1cm} (2-28)

The Biot number is much less than 0.1. So, the lumped heat capacity is valid for the heat transfer calculation.

Sometimes, particles are not completely melted so the heat flux is:

\[ m_p C_p \frac{dT_p}{dt} = \pi D_p^2 \dot{q}'' \quad (for \quad T_p \neq T_m) \]  \hspace{1cm} (2-29)
When the particle is at melting temperature it can experience partial melting, the heat transfer is used to melt the particle and the temperature does not change at this step. So we expect to have partial melting in the particle trajectory. A one-dimensional model can be used for particle melting distribution. Particles are of a spherical shape.

\[ m_p L_m \frac{d(MI)}{dt} = \pi D_p^2 \dot{q}'' \quad (for \ T_e \neq T_m) \tag{2-30} \]

where \( \dot{q}'' \) is the heat flux at the particle surface and \( MI \) is the melting index (the melted mass ratio of particle). Figure 2-5 shows the melting part and solid part of a particle.

Zhang et al. [41] introduced a new method to calculate the melt fraction of in-flight particles. They defined the melting index (MI) concept as follows:

\[ MI = \frac{H_p}{m_p} - h_{sm} \tag{2-31} \]

where \( \frac{H_p}{m_p} = h_p \) is the average enthalpy of the particle, \( H_p \) is the total enthalpy of the particle and \( m_p \) is the mass of the particle, and \( h_{sm} \) is the enthalpy of the particle at the melting temperature when it is still completely solid. By using the melting index (MI) definition, if MI is larger than 1, then the particle is completely molten, if it is less than 1, the particle is partially molten.

A turbulent flow has high velocity fluctuations and instabilities which can affect the particle motion and heating. There are two practical methods to model turbulent dispersion for discrete phase: the Discrete Random Walk Model and Particle Cloud Tracking. In a turbulent flow, velocity fluctuations can affect the particle and it may produce some secondary fluctuations in particle velocity. The problem is that in a turbulent model such as \( k - \varepsilon \), the precise value of velocity is not calculated, rather an average value of velocity is calculated. Therefore, a new approach is needed to calculate the effects of velocity fluctuation on particles in the turbulent model. The stochastic tracking model and particle cloud are the two most practical models to simulate particles in a turbulent flow. The stochastic tracking (Random Walk) model predicts the effect of instantaneous turbulent velocity fluctuations on the particle movement by using stochastic methods. The particle cloud model uses Gaussian probability density functions around the average
particle velocity. The stochastic tracking model, however, models the velocity fluctuations by using the mean average gas velocity and instantaneous value of the fluctuation gas flow velocity. The instantaneous velocity is:

\[ u = \bar{u} + u' \]

Figure 2-5. Schematic of partially melted particle

The stochastic model calculates the turbulent particle dispersion by using instantaneous velocity \( \bar{u} + u'(t) \) in the particle movement equation integration for individual particles. So, the random effects of turbulence on particle movement are calculated. Next, the instantaneous velocity must be determined. The stochastic tracking model will be used to predict the instantaneous velocity. The discrete random walk model assumes velocity fluctuations are discrete piecewise constant functions of time. These random values are calculated by using the characteristic of eddies and remain constant over each time step. This method is not reliable for particles with diameters less than a few microns.
The Particle Cloud Tracking is not reliable for unsteady simulations, then Random Walk model was used for this study.

We need to define a new concept: Lagrangian integral time $T_L$. It is estimated as:

$$T_L = C_L \frac{k}{\epsilon} \quad 2-33$$

where $k$ is the turbulent kinetic energy, $\epsilon$ is the turbulent dissipation and $C_L = 0.3$ for k-$\epsilon$ model.

To use Random Walk model we need to assume eddies are from a Gaussian probability distribution and we also need to define eddy life time. The life time for the eddy is $\tau_e$ [70].

$$\tau_e = 2T_L \quad 2-34$$

Velocity fluctuations are defined:

$$u' = \zeta \sqrt{u'^2} \quad 2-35$$

$$v' = \zeta \sqrt{v'^2} \quad 2-36$$

$$w' = \zeta \sqrt{w'^2} \quad 2-37$$

where $\zeta$ is a number which is normally distributed and $u'$, $v'$, and $w'$ are velocity fluctuations, we can calculate them form:

$$\sqrt{u'^2} = \sqrt{v'^2} = \sqrt{w'^2} = \sqrt{2k/3} \quad 2-38$$

where $k$ is turbulent kinetic energy. So, now we have the tools to calculate the velocity fluctuations and their life time for particle trajectory.

Figure 2-7 shows a schematic of the plasma discharge domain and Figure 2-6 provides the mesh domain created for simulation. The mesh size is 400,000 hexagonal structured cells for a finite...
volume method simulation. For this part, the simulation was assumed to be done in atmospheric conditions so atmospheric species (oxygen and nitrogen) and pressures of far-field boundary conditions were considered. The plasma jet discharge was solved twice: once with substrate and once without substrate. The substrate was set at 12-cm and 15-cm distances from the torch outlet. This model was solved with the exact time steps of the DC plasma torch set equal to $10^{-5}$s. The torch outlet temperature, velocity, and turbulence characteristic distributions at each time step were obtained and set as inlet boundary conditions of the plasma discharge model. Therefore, the mass flow rate is exactly the same as the torch inlet and is equal to 60 slpm. Figure 13 shows schematic of the simulation domain. The numerical domain is a cylinder with R=5cm and L=12,15cm. The length may be subject to change depending on the distance of the substrate from the torch outlet.

Figure 2-6. Mesh network of the plasma torch outlet and substrate
Figure 2-7. Schematic of the plasma torch outlet and substrate

Figure 2-8. Boundary conditions of the plasma jet domain outlet and substrate
Chapter 3
Experiments

3 Experiments

The experimental test set up consisted of an SG-100, a Blue torch, and an oscilloscope. Several series of experiments were conducted using this set up. The experimental conditions and results are explained in the following sections.

3.1 Experimental methodology

An SG-100 torch designed by Praxair [65] and a Blue torch designed by the Center for Advanced Coating Technologies (CACT) [79] were used for this study. The experiments included three scenarios: a pure argon in the SG-100 torch, an argon-hydrogen mixture (54 slpm argon and 6 slpm hydrogen) in the SG-100 torch, and a CO2 based mixture in the Blue torch. Moreover, nickel particles were injected into the SG-100 torch and the velocity and temperature of the particles were measured with a DPV 2000 [80]. The operating conditions for the torches are shown in Table 3, Table 4, and Table 5. An oscilloscope was connected to the torch and recorded the voltage fluctuations. The torch was set up and the experiment would begin by turning on the torch. After a minimum of five minutes, the torch would reach a semi-steady state. It was in this state that the values of the voltage drop and the torch thermal efficiency were measured.

Table 3-1. Operating conditions for pure argon in the SG-100 torch

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Power (kW)</th>
<th>Electric current (A)</th>
<th>Ar (slpm)</th>
<th>Cooling power (kW)</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>21.0</td>
<td>500</td>
<td>60</td>
<td>12.2</td>
<td>42.0</td>
</tr>
</tbody>
</table>

Table 3-2. Operating conditions for argon-hydrogen mixture in the SG-100 torch

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Power (kW)</th>
<th>Electric current (A)</th>
<th>H2 (slpm)</th>
<th>Ar (slpm)</th>
<th>Cooling power (kW)</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>78</td>
<td>31.2</td>
<td>400</td>
<td>6</td>
<td>54</td>
<td>15.4</td>
<td>50.6</td>
</tr>
</tbody>
</table>
Table 3-3. Operating conditions for CO₂ mixture in the Blue torch

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Power (kW)</th>
<th>Electric current (A)</th>
<th>CO₂ (slpm)</th>
<th>CH₄ (slpm)</th>
<th>Ar (slpm)</th>
<th>Cooling power (kW)</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>128</td>
<td>38.4</td>
<td>300</td>
<td>10.5</td>
<td>3</td>
<td>12</td>
<td>19.2</td>
<td>50.0</td>
</tr>
</tbody>
</table>

Figure 14 shows a schematic of the experimental setup. The torch is wired to the oscilloscope, which records voltage fluctuations while the torch is operating. Using the data from the oscilloscope, the voltage fluctuations over time were measured. Specific parameters of the torch operating condition (e.g., average voltage, cooling load) were measured.

![Figure 3-1. Schematic of experimental set up](image)

Table 6 and Table 7 show the particle injection operating conditions in the cases of pure argon and the argon-hydrogen mixture.

Table 3-4. Operating conditions for nickel particle injection in pure argon with argon carrier gas

<table>
<thead>
<tr>
<th>Mean size(µm)</th>
<th>Size range (µm)</th>
<th>Carrier gas (slpm)</th>
<th>Particle flow (gr/min)</th>
<th>Distance from torch outlet (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>65</td>
<td>45-90</td>
<td>5.9</td>
<td>30</td>
<td>15</td>
</tr>
</tbody>
</table>
Table 3-5. Operating conditions for nickel particle injection in the Ar-H₂ mixture with argon carrier gas

<table>
<thead>
<tr>
<th>Mean size(µm)</th>
<th>Size range (µm)</th>
<th>Carrier gas (slpm)</th>
<th>Particle flow (gr/min)</th>
<th>Distance from torch outlet (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>20-35</td>
<td>5</td>
<td>24</td>
<td>12</td>
</tr>
</tbody>
</table>

3.2 Fast Fourier Transform analysis of voltage fluctuations

A Fast Fourier Transform analysis of the voltage fluctuations was calculated with MATLAB. The following graphs show the pick points of the dominant frequency of the voltage fluctuations.

![FFT result of arc voltage](image)

Figure 3-2. Fast Fourier Transform results for voltage fluctuations for SG-100 torch, pure argon, 600 A and 60 slpm

By employing the Fast Fourier Transform to process the voltage drop, we can calculate the dominant frequency. The voltage fluctuations will later be used in the numerical model.
Chapter 4
Simulations

4 Simulations

It is necessary to determine which discretization methodology will be used to discretize the sets of partial differential equations (PDEs). A control volume discretization methodology is best suited for simulating fluid flow equations because it satisfies conservation equations such as the conservation of energy, the conservation of mass, and the conservation of electric current [43,68].

In control volume discretization methodology, the system under study is partitioned into miniscule portions of volume. These portions are small enough that the fluid characteristics do not change substantially from one boundary to the opposite boundary of these portions. FLUENT™ is a software widely known for its performance in successfully simulating fluid flows using the control volume discretization methodology [70]. Therefore, FLUENT™ was selected to simulate the fluid flow in the system for this study. FLUENT™ discretizes the selected set of coupled (PDEs) over the control volumes that the meshing networks have generated. The discretized set of PDEs are now a set of algebraic equations. The software takes into consideration the boundary conditions and initial conditions and solves the aforementioned set of algebraic equations for each control volume once in each iteration. The momentum equations are solved first and the results are incorporated in SIMPLE’s algorithm for pressure corrections. The iterations are repeated until the results converge to a final series of results which show the characteristics of the fluid flow over the entire domain under study [68].

The convergence is assessed at the end of each iteration based on a residual scale (residual value). This means that the absolute value of all of the errors in all equation parameters over all control volumes, when compared to reference values, should be within an acceptable limit set by the researcher. In this study, the residual value was set to $10^{-8}$ for density, and to $10^{-6}$ for all other parameters. The model was considered numerically converged when energy, mass, and electric current were conserved in the model, and the residual values were below the acceptable limits.

The numerical model has three parts: inside the torch, the plasma jet stream, and the particle injection. The numerical model of the DC plasma torch was solved. Then, the torch outlet
temperature, velocity and turbulent characteristics were obtained at each time step. The outlet results were used at the plasma jet stream inlet and the model was solved with the same time step. There is no difference between performing the calculation in this staggered manner, or in solving the whole model at once. If we had modeled the entire configuration in one model, all parameters would also be set at each time step and so, there is no difference between the two models. The decision to solve the model in different stages was made as it provided more flexibility for debugging the model. Table 4-1 shows the steps of the numerical model. Later, the steps will be discussed in more detail.

Table 4-1. Steps of numerical modeling

<table>
<thead>
<tr>
<th>Item number</th>
<th>Simulation series title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Steady state simulations for finding voltage drop and thermal efficiency for a range of arc root attachment radius and arc length</td>
</tr>
<tr>
<td>2</td>
<td>Comparing the steady state numerical results with experimental results to find the arc radius root attachment and length range</td>
</tr>
<tr>
<td>3</td>
<td>Unsteady state simulations for finding the effects of the arc instabilities when the arc moves in a sinusoidal manner</td>
</tr>
<tr>
<td>4</td>
<td>Unsteady state simulations for finding the voltage drop and thermal efficiency when arc moves in a half sinusoidal – half random manner</td>
</tr>
<tr>
<td>5</td>
<td>Unsteady state simulations for finding the voltage drop and thermal efficiency when arc moves based on real voltage fluctuations</td>
</tr>
<tr>
<td>6</td>
<td>Outlet plasma jet stream simulations without particle injection using unsteady state results for simulating the outlet plasma jet stream to study instability of the plasma jet</td>
</tr>
<tr>
<td>7</td>
<td>Outlet plasma jet stream simulations with particle injection using an average integral of results to simulate outlet plasma jet stream</td>
</tr>
<tr>
<td>8</td>
<td>Outlet plasma jet stream simulations with particle injection using unsteady state results for simulating the outlet plasma jet stream</td>
</tr>
</tbody>
</table>
4.1 Arc Movement Models

This project was of a hierarchical nature. Therefore, multiple series of simulations needed to be run in order to get to the final simulation cases. The evolution of the simulation series is shown in Table 4-1.

There are several sources of instability in the fluid flow inside the torch. In order to study these instabilities, we first must establish a grounding upon which we will build future simulation cases that will focus on the main source of instability and investigates its effects. The foundational simulations are set to be comparable to the experimental conditions. This founding case is based upon a steady state fluid flow. Table 4-2 and Table 4-3 list all of the assumptions made in these steady state simulations.

Table 4-2. Operating conditions for the pure argon steady state simulations

<table>
<thead>
<tr>
<th>Assumptions:</th>
</tr>
</thead>
<tbody>
<tr>
<td>The gas inside the torch is pure argon</td>
</tr>
<tr>
<td>The arc is stable and it does exhibit any fluctuations</td>
</tr>
<tr>
<td>LTE with sheath layer</td>
</tr>
<tr>
<td>Turbulent model used in this simulation is $k - \varepsilon$</td>
</tr>
<tr>
<td>The electrical current is set at constant 500 A (typical current amperage of a SG-100 in industrial applications)</td>
</tr>
<tr>
<td>The inlet mass flow rate is set at constant 60 slpm (typical mass flow rate of a SG-100 in industrial applications)</td>
</tr>
</tbody>
</table>

In the steady state simulation, it was assumed that the fluid flow inside the torch is steady state. This means that the fluid flow, once fully developed, will not change over time. In order to get a steady state fluid flow, all of the sources of instability inside the torch should be assumed to be constant over the time step. Although the arc is assumed to be stable, the arc length (determined by the arc root attachment point) and radius are set to a different value at each test case. In other words, a series of simulations was run and in each case the location of the arc root attachment was set at a different point on the wall (hence different arc length). Also, the same series of simulations
was run while setting the radius of the arc to different values (see Figure 4-1). At the end of each simulation, the voltage drop and thermal efficiency (total thermal energy carried by the fluid at the outlet / total thermal energy given to the fluid in the inside the torch) were exported. As a result, a series of data points representing the voltage drop and thermal efficiency of the fluid flow over a range of arc length and arc radius were generated. By analyzing these series, it is possible to study the voltage drop and thermal efficiency at different arc lengths and radii.

In the experiments, the thermal efficiency as well as the voltage fluctuation over time were measured. These two parameters are key to finding the matched arc radii and arc length ranges.

Table 4-3. Operating conditions for the argon-hydrogen mixture steady state simulations

<table>
<thead>
<tr>
<th>Case: steady state simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumptions:</td>
</tr>
<tr>
<td>The gas inside the torch is mixture of argon and hydrogen</td>
</tr>
<tr>
<td>The arc is stable and it does exhibit any fluctuations</td>
</tr>
<tr>
<td>LTE with sheath layer</td>
</tr>
<tr>
<td>Turbulent model used in this simulation is $k - \varepsilon$</td>
</tr>
<tr>
<td>The electrical current is set at constant 400 A (typical current amperage of a SG-100 in industrial applications)</td>
</tr>
<tr>
<td>The inlet mass flow rate is set at constant 54 slpm argon and 6 slpm hydrogen (typical mass flow rate of a SG-100 in industrial applications)</td>
</tr>
</tbody>
</table>

Figure 4-2 shows the voltage drop versus arc length for different arc radii. As shown in this figure, the voltage drop increases as the arc length increases and decreases when the arc radius increases. When arc length is longer, the average voltage drop is larger.

Figure 4-3 demonstrates the arc power for a series of different arc lengths and radii. As expected, increasing the arc length increases the arc power because the electric current remains constant.
a) Two cases of same arc radius but different arc length  
b) Two cases of same arc length but different arc radius

Figure 4-1. Arcs of different lengths and radii

Figure 4-2. Effect of anode arc root radius and length on voltage drop for pure argon in steady-state simulations
The thermal efficiency of the torch is highly dependent on the arc length. Figure 4-4 shows the thermal efficiency of the torch at various arc lengths and radii. As shown in Figure 4-4, the thermal efficiency increases when the arc length and/or the arc radius increases.

As explained above, a series of analogous simulations and experiments was run. The purpose of these actions are explained below where the simulation results and experimental measurements are overlaid and compared. When comparing the experimental voltage fluctuation with the simulation voltage drops, all the radii can be chosen, but the value chosen for the radius should satisfy the torch thermal efficiency (42%) when it fluctuates between the arc length bands. In other words, the chosen radius should provide the average mentioned thermal efficiency when it satisfies the voltage fluctuation by the change of the arc length. In order to meet this requirement, the values selected were R=1.8mm and L=9-11mm.
As explained earlier in this chapter, the simulation of the unsteady-state flow with arc instability which is the focus of this project, needs to be solved in a hierarchical manner. This means that first a decision must be made about the arc root attachment point, and then the best approximation for the range of the arc length and radius must be determined. These two values are then used as an input into future simulations where the unsteady fluid flow is studied.

Overlaying the voltage drop and thermal efficiency steady-state simulation results, over experimental findings (see Figure 4-5 and Figure 4-6 below), we can see that the best match between experimental results and simulation results occurs when the arc radius is 1.8mm and the arc length is 9-11mm. In other words, the simulation results best represent the reality when the arc radius is 1.8mm and the arc length is 9-11mm.

Figure 4-4. Effect of arc radius and length on torch thermal efficiency for pure argon in steady-state simulations.
The observation that the simulation results best match experimental results at $R=1.8\text{mm}$, and $L=9-11\text{mm}$ for the pure argon case is consistent with the findings reported by Ramachandran and Selvan et al [81,82].
4.2 Unsteady state simulations

Having the arc root attachment point and arc root attachment radius, we can now run the simulations for unsteady state situations. It should be noted that although the arc radius and range of arc length are considered to be known, they are unstable through time. This means that the arc root attachment moves through time and its movement is one of the main factors contributing to arc instability. Previous observations have shown that arc root attachment point movement can be described as modular (periodical movements). It has also been observed that one of the main modes of this modular movement is in fact sinusoidal movements.

The sinusoidal movement of the arc root attachment point was incorporated into the simulation set up by a complicated user defined code that was implemented in FLUENT [70]. Figure 4-7 shows a schematic of this movement. The results of sinusoidal arc movement are not presented in this thesis.

![Schematic of Sinusoidal Movement](image)

Figure 4-7. Sinusoidal movement of the arc root attachment point

Although sinusoidal arc fluctuation would help to explain temperature and velocity change at the torch outlet, we need a more accurate model to simulate the arc movements inside the torch.
Applying a sinusoidal model inside the torch has two main problems: the arc restrike cannot be explained (when the arc jumps to the opposite side the anode wall [6,8,28-30,32,33,37]), and it predicts a voltage fluctuation which is almost sinusoidal while experimental data show it to be in a restrike mode of oscillation [8,37].

It was explained how the arc root attachment point was modeled as a sinusoidal movement. With further study of the simulation results and experimental observations, it became clear that a better model for arc root attachment point movement could be postulated. It is proposed that the arc movement can be modeled as a sinusoidal-random combination movement [8,37]. The arc strikes the anode and establishes a new root attachment point (minimum length point), then the attachment point starts to move towards the torch outlet. As soon as the root attachment point reaches a point that can be considered the pick point of a sinusoidal movement (maximum length point), the arc detaches and strikes the anode at a random point on the opposite side of the anode wall (at a different $\theta$) with the minimum arc length. Figure 4-8 shows a schematic of this movement.

![Figure 4-8. Sinusoidal-random movement of arc root attachment point](image)

To obtain more accurate results, the target of the final stage of this study is to model results which exactly match the real voltage fluctuations. To accomplish this, the arc root attachment radius and
the range of the arc length were obtained from the steady state simulations. As explained before, the arc length and radius were found by means of the voltage drop and thermal efficiency found via experimental results. After the arc root attachment radius and the range of arc length were found, several cases were solved to get a series of voltage against arc length. By using the experimental voltage drop over time, the arc length over time can be found. This is the basis of the last stage of this project. By using this method, it is proposed that the obtained voltage fluctuation will be closely correlated with that of the experimental results.

This simulation will be done for the mixture of argon and hydrogen since there is lack of information about plasma characteristics for this important mixture. Figure 4-9 shows the experimental voltage fluctuation over time for the mixture of argon and hydrogen.

Figure 4-10 and Figure 4-11, respectively, show the voltage drop and thermal efficiency of the torch. By using the experimental voltage fluctuations seen in Figure 4-9, and comparing the results, we can conclude that the arc radius is 0.8mm and the arc length is L=4-11mm. These values correspond to those reported by Collares and Pfender [83].

Figure 4-12 shows extra simulations which were done to find the voltage drop for a greater number of arc lengths in order to find the arc length based on the voltage fluctuations.

![Experimental voltage fluctuation for the argon-hydrogen mixture and 400 A](image)
Figure 4-10. Voltage drop of numerical simulations for different arc lengths and radii for the argon-hydrogen mixture and 400 A in steady-state simulations.

Figure 4-11. Thermal efficiency of numerical simulations for different arc lengths and radii for the argon-hydrogen mixture and 400 A in steady-state simulations.
Figure 4-12. Voltage drop for numerical simulations for the argon-hydrogen mixture in steady-state simulations.
Chapter 5
Results and discussion

5 Results and discussion

5.1 Argon plasma inside the torch

For industrial applications, an SG-100 torch’s electrical current is set at a constant value of 500 A, and the inlet mass flow rate is set to 60 slpm of pure argon. Figure 5-1 to Figure 5-9 show numerical results at various cross sectional slices along the torch.

Figure 5-1 shows the Joule heating on x-z plane at different time steps. Heat generation is maximum closest to the cathode, where the electric current is maximum, and also it is high close to the anode root attachment point, where the electric current is high. Inside the arc, heat generation is high, however, outside of the arc, heat generation is negligible. Figure 5-7 also shows the Joule heating at different cross section of the torch.

Figure 5-2 and Figure 5-4 show the temperature and velocity variations at the torch outlet over time. Results show that the maximum, and the position, of the temperature and velocity change dramatically over time. This can affect the particle heating.

Figure 5-3 and Figure 5-5 present the temperature and velocity contours on x-z plane at different time steps. The temperature is close to 30kK at the cathode and it is also high near the anode surface at the root attachment point (15kK) because it is at those two areas that the heat generation is maximum. This can be explained by considering the fact that the maximum temperature occurs where the thermal energy due to Joule heating is maximum. Joule heating is influenced by two parameters: i) electrical conductivity, and ii) the magnitude of the electric field. The electrical conductivity of the fluid is small on the wall, while the magnitude of the electric field is stronger. Therefore, the maximum heat generation (Joule heating) occurs at the point where the product of electrical conductivity times the square of the electric field intensity is at maximum, close to the cathode. Due to Lorentz force effects, the maximum temperature occurs only close to the cathode and not exactly in the center.
As expected, due to the arc moving inside the torch, the velocity at the torch outlet also fluctuates. The velocity fluctuates between 870 to 1120m/s (almost 30%) which causes the particles to experience different gas velocities at different positions and times. Velocity is more sensitive than temperature to arc fluctuations. The maximum velocity occurs close to the torch outlet. It can be seen that the outlet velocity profile is more uniform than the temperature profile.

Figure 5-6 presents the electric current density at different cross sections of the torch. Results shows that close to the cathode and anode, the electric current is maximum.

Figure 5-8 and Figure 5-9 show temperature and velocity profiles at different cross sections at different distances from the cathode. Results show temperature and velocity dramatically increase close to the arc root. Also, as shown in the figures, when the distance from the cathode increases, the velocity and temperature profiles show a tendency to remain uniform. Again, the outlet velocity profile is observed to be more uniform than the temperature profile. Due to heat conduction, the maximum temperature decreases as the distance from the cathode increases. Since velocity depends on density, the change in the velocity profile is slower and smoother. Therefore, we expect to have maximum velocity close to the torch outlet.

Turbulence kinetic energy generation is shown in Figure 5-10. Turbulence generation is highly dependent on the velocity gradient. As the velocity at the torch outlet is higher, we expect there to be a higher gradient at that location. Turbulence kinetic energy generation is one of the main factors affecting particle acceleration and heating. Thus, it is very important to take into account the turbulence kinetic energy generation for particle injection modeling.
a) at $t = 20 \mu s$

b) at $t = 200 \mu s$

c) at $t = 800 \mu s$

d) at $t = 1200 \mu s$

Figure 5-1. Joule heating contours on z-x plane over time
Figure 5-2. Temperature contours at outlet over time

(a) at $t = 20 \mu s$
(b) at $t = 200 \mu s$
(c) at $t = 800 \mu s$
(d) at $t = 1200 \mu s$
Figure 5-3. Temperature contours on x-z plane over time.
Figure 5-4. Velocity contours at the torch outlet over time

a) at $t = 20 \mu s$

b) at $t = 200 \mu s$

c) at $t = 800 \mu s$

d) at $t = 1200 \mu s$
Figure 5-5. Velocity contours on x-z plane over time
Figure 5-6. Electric current density contours at various cross sectional slices along the torch at $t = 300 \, \mu s$

Figure 5-7. Joule heating contours at various cross sectional slices along the torch at $t = 300 \, \mu s$
Figure 5-8. Temperature contours at various cross sectional slices along the torch at $t = 300 \mu s$

Figure 5-9. Velocity contours at various cross sectional slices along the torch at $t = 300 \mu s$
Figure 5-10. Turbulence kinetic energy contours at various cross sectional slices along the torch at \( t = 300 \mu s \)

Figure 5-11 shows the voltage drop over time for the unsteady state numerical model. This voltage drop has been compared with the experimental voltage drop in Figure 5-12. Results are in a very good agreement and coefficient of determination (\( R^2 \)) is 0.96.

Figure 5-13 and Figure 5-14 show the average velocity and temperature at the torch outlet over time. Results show that as the arc fluctuates, the temperature and velocity will fluctuate at the torch outlet. This high fluctuation (15%) can change particle heating history.

Figure 5-16 and Figure 5-17 show the velocity and temperature at the centerline at the torch outlet. The velocity fluctuation at the outlet is higher than the temperature fluctuation at the outlet. This is due to several reasons. The Lorentz force is calculated for the momentum equation which needs the value of the magnetic field. The magnetic field is a gradient of the magnetic potential vectors. Therefore, by changing the size and position of the arc, the Lorentz force will change. Moreover, the momentum equation is non-linear and as such it is more sensitive to source terms (e.g., Lorenz force). Furthermore, based on the properties of argon, the gas net emission coefficient is high, and
the density of the gas is the lowest value at high temperatures, while the specific heat of gas experiences its highest value at high temperatures (8-15kK). Due to these facts, the temperature value is very stable close to 8-15kK and it will not change significantly even with some change in the energy source term due to arc movement. This is the most significant reason that there is more fluctuation in the velocity (more than 25%) than in the temperature (14 %) at the torch outlet.

Results presented in Figure 5-13 and Figure 5-16 show that the temperature at the torch outlet at the centerline is much higher than the average temperature. This occurs due to two main reasons. First, the arc has an L-shape. Then, if we integrate Joule heating over time to find the average over time, the maximum occurs at the centerline because the arc fluctuates on the anode surface in theta direction. Therefore, the only area which always has high Joule heating is close to the cathode at the centerline. Second, there is an effective cooling system around the anode that cools down the gas close to the anode surface. For the same reasons, velocity at the torch outlet at the centerline is much higher than the average temperature (Figure 5-14 and Figure 5-16). Figure 5-17 shows thermal efficiency of the torch over time. Results show the average thermal efficiency over time is matched with the experimental thermal efficiency.

![Voltage drop versus time for pure argon](Figure 5-11)
Figure 5-12. Comparison of numerical and experimental voltages versus time for pure argon.

Figure 5-13. Mass weighted average temperature at the torch outlet versus time for pure argon.
Figure 5-14. Average velocity at the torch outlet versus time for pure argon

Figure 5-15. Temperature at the centerline at the torch outlet versus time for pure argon
Figure 5-16. Velocity at the centerline at the torch outlet versus time for pure argon

Figure 5-17. Thermal efficiency of the torch versus time for pure argon
5.2 Argon-hydrogen plasma inside the torch

The present work is novel in incorporating an argon – hydrogen mixture in its simulation. Table 5-1 shows the operating conditions for argon-hydrogen mixture.

Table 5-1. Operating conditions for argon-hydrogen mixture in the SG-100 torch

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Power (kW)</th>
<th>Electric current (A)</th>
<th>H2 (slpm)</th>
<th>Ar (slpm)</th>
<th>Cooling power (kW)</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>78</td>
<td>31.2</td>
<td>400</td>
<td>6</td>
<td>54</td>
<td>15.4</td>
<td>50.6</td>
</tr>
</tbody>
</table>

Figure 5-18 and Figure 5-19 present the temperature and velocity contours on x-z plane at different time steps. The temperature is close to 29500K at the cathode and it is very high near the anode surface at the root attachment point because, at those two areas, Joule heating is at maximum.

The velocity is more sensitive when hydrogen is added to the plasma gas. Because the gas density is dramatically decreased at high temperatures (T>10000K), and as this torch has higher power and lower mass flow rates compared to the pure argon plasma torch, then the temperature at the torch outlet is higher.

The simulation results show that a plasma of argon and hydrogen mixture is a better conductor of heat compared to other mixtures used in plasma torches. Moreover, the temperature and velocity profiles are more evenly distributed compared to those of the plasma medium constituted of pure argon. One reason for this is that hydrogen molecules are much smaller than argon molecule and their movements are fast and the other reason is the reaction of dissociation effect. Therefore, their heat transfer coefficient is much higher than that of argon. Also, argon-hydrogen plasma exhibits greater voltage fluctuations and thus the arc experiences more significant length changes [84,85].

Figure 5-20 shows numerical and experimental voltage over time for the argon-hydrogen mixture. The voltage drop over time for the argon-hydrogen mixture has been calculated by using point by point matching, which is explained in the chapter describing the numerical model. The results show better correlation with measurements. In the present work, coefficient of determination (R^2)
is 0.982, while for pure argon this value was 0.961. It can be concluded that these simulation settings result in more accurate findings which are in better agreement with experimental results.

Figure 5-21 and Figure 5-22 show the average temperature, and the temperature at the centerline at the torch outlet, over time. Results show that as the arc fluctuates, the average temperature fluctuates by up to 20%.

The velocity and temperature can be integrated at the torch outlet over time to calculate the mean velocity and temperature at the torch outlet over time for the argon-hydrogen mixture. The results are shown in Figure 5-21 and Figure 5-23.

Figure 5-23 and Figure 5-24 show the average velocity at the centerline at the torch outlet. The velocity fluctuates by more than 30%. The velocity fluctuation at the outlet is higher than the temperature fluctuation at the outlet. Thermal efficiency of the torch is shown in Figure 5-26. Average thermal efficiency over time is in a good agreement with the experimental thermal efficiency. But, the instantaneous thermal efficiency is highly fluctuating because the voltage highly fluctuates.
Figure 5-18. Temperature contours on x-z plane over time for the argon-hydrogen mixture

Figure 5-19. Velocity contours on x-z plane over time for the argon-hydrogen mixture
Figure 5-20. Comparison of numerical and experimental voltage versus time for the argon-hydrogen mixture

Figure 5-21. Average temperature at the torch outlet versus time for the argon-hydrogen mixture
Figure 5-22. Temperature at the centerline at the torch outlet versus time for the argon-hydrogen mixture

Figure 5-23. Average velocity at the torch outlet versus time for the argon-hydrogen mixture
Figure 5-24. Velocity at the centerline at the torch outlet versus time for the argon-hydrogen mixture

Figure 5-25. Thermal efficiency of the torch over time for argon-hydrogen
5.3 Blue Torch

Up to this point in the study, the focus has been on the SG-100 torch as it is a torch popularly used in industry. Recently, a new design of plasma torch has been proposed for industry use known as the Blue torch. In order to evaluate the performance of the Blue Torch, the SG-100 was replaced with a Blue torch in the developed models and simulation set up. By incorporating a step in the design of this torch, the arc root attachment point has been transferred downstream. The increase in arc length results in an increase in torch power. The existence of the step also prevents the cold gas from penetrating into the boundary layer. This means that the zone immediately after the step, is always ready for arc discharge as it has a high temperature boundary layer and thus high electrical conductivity. Incorporating this step allows control over arc length and the ability to secure it to be longer than a set length, which is the distance of the step to the cathode.

Table 5-2. Operating conditions for CO2 based mixture in the Blue torch

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Power (kW)</th>
<th>Electric current (A)</th>
<th>CO₂ (slpm)</th>
<th>CH₄ (slpm)</th>
<th>Ar (slpm)</th>
<th>Cooling power (kW)</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>128</td>
<td>38.4</td>
<td>300</td>
<td>10.5</td>
<td>3</td>
<td>12</td>
<td>19.2</td>
<td>50.0</td>
</tr>
</tbody>
</table>

The velocity and temperature contours are shown in Figure 5-26 and Figure 5-27. The maximum temperature is 19kK and occurs close to the cathode. Due to the high enthalpy and mass flow rate (compared to argon plasma), the maximum temperature is much lower.

Figure 5-28 shows the experimental voltage fluctuations and numerical voltage. Results are in good agreement with R²=0.976. The velocity and temperature fluctuations at the torch outlet are shown in Figure 5-29 to Figure 5-32. As Figure 5-31 and Figure 5-32 illustrate, the velocity fluctuations are less than 10%. Temperature fluctuations are 2%. These velocity and temperature fluctuations are rather low compared to the case with pure argon plasma, and compared to the hydrogen-argon mixture plasma. The main reasons for this are that the gas mixture is high enthalpy and the Blue torch length is 56.6 mm but the SG-100 length is 32 mm. Therefore, the mixing of the high temperature zone (close to the arc root attachment) with the low temperature zone overlaps.
more in the SG-100 torch. This effective mixing of hot and cold fluid has a stronger effect on the
temperature and velocity profiles than the high voltage fluctuations which makes the temperature
and velocity profile uneven. In other words, although the voltage fluctuations are higher, the
velocity and temperature fluctuations at the torch outlet are lower due to the more effective mixing
of high and low temperature zones. This means that the temperature and velocity profiles over
time are constant compared to previous cases. This result is favorable as we wish to create uniform
conditions for particles injected into the stream for melting and deposit a uniform coating on the
substrate over any period of time. If the particles all experience similar conditions, they will be
evenly heated, melted and accelerated and hit the substrate at a similar speed and temperature.

At high temperatures (7000-10000 K), such as at the torch outlet, plasma has a high specific heat.
No large fluctuations of temperature are observed at the torch outlet. Gas enthalpy, however,
experiences fairly large changes. Figure 5-34 shows the specific heat of plasma versus temperature.
Specific heat experiences maximum of 25000 J/kgK in temperature range from 7000 to 8000. It
means a large change in plasma enthalpy does not result in large temperature change.

Further study shows that the effective mixing that comes with a longer torch, results in lower
thermal efficiency of the torch. Figure 5-35 shows the fluctuations of average temperature along
the torch. Figure 5-36 shows changes in the average enthalpy of the plasma along the torch. As
shown in these two figures, the plasma has the highest enthalpy at the cross section immediately
after the arc root attachment point, which is due to the large thermal energy released into the fluid
due to the creation of the arc. Past this point, the enthalpy of plasma changes from $45 \times 10^6$ to
$25 \times 10^6$ J/kg at the torch outlet. The decrease in enthalpy is due to heat being transferred through
the wall and to radiation. The huge fall in enthalpy shows that although increasing the length of
the torch elevates the mixing of hot and cold zones, it also causes a large drop in the thermal energy
within the torch resulting in lower efficiency. Therefore, it is better to design torches with higher
than 50% thermal efficiency at the cost of decreasing the torch length. Figure 5-33 shows thermal
efficiency of Blue torch over time.
Figure 5-26. Temperature contours on x-z plane over time for the Blue torch

Figure 5-27. Velocity contours on x-z plane over time for the Blue torch
Figure 5-28. Comparison of numerical and experimental voltage versus time for the argon-hydrogen mixture for the Blue torch

Figure 5-29. Average temperature at the torch outlet versus time for the Blue torch
Figure 5-30. Maximum temperature at the torch outlet versus time for the Blue torch

Figure 5-31. Average velocity at the torch outlet versus time for the Blue torch
Figure 5-32. Maximum velocity at the torch outlet versus time for the Blue torch

Figure 5-33. Thermal efficiency of the torch versus time for the Blue torch
Figure 5-34. Specific heat versus temperature for the mixture CO$_2$ based mixture

Figure 5-35. Average temperature along the axis of Blue torch
5.4 Plasma jet simulations for pure argon

The results for the plasma torch discharge simulation without substrate are presented in Figure 5-37 and Figure 5-38. In this model, it is assumed that the end of the domain is open and the boundary condition is atmospheric. The velocity and temperature contours show the instability of the plasma jet due to arc instability. These results show how arc instability inside the torch can produce jet movement and instability. By increasing the jet movement’s instability, the turbulence kinetic energy production is also increased, which is very important to particle trajectory.

Figure 5-39 and Figure 5-40 show the contours of temperature and velocity in the plasma discharge with substrate. Modeling the substrate changes the flow direction at the end of the domain, close to the substrate, and forms a stagnation point (Figure 5-42a) with a relative maximum temperature (Figure 5-42b). In this study the plasma jet discharged in atmospheric air and species equations were solved. Figure shows contours of volumetric fraction of argon and oxygen in plasma jet. The shear layer between cold and hot gas and plasma jet fluctuations and also molecular diffusion mix air with the plasma gas.
Figure 5-37. Plasma jet temperature contours without substrate at different times
Figure 5-38. Plasma jet velocity contours without substrate at different times
Figure 5-39. Plasma jet temperature contours with substrate at different times.
Figure 5-40. Plasma jet velocity contours with substrate at different times

t = 260µs  

t = 290µs
Figure 5-41. Volumetric fraction of species in plasma jet with substrate for pure argon plasma at t=2 ms on XZ plane.
Figure 5-42. a) Streamlines with substrate, b) contour of temperature at the substrate
6 Particle Injection Simulation Results

At this point in this study, we have a good understanding of the fluid flow inside and outside of the torch. The next step is to examine how the coating particles interact with this plasma jet stream. This series of simulations involved injecting nickel particles (a material commonly used in plasma coating) into the plasma jet stream outside of the torch. Once again, the simulations relied on a series of complicated user defined codes incorporated into FLUENT™. Table 6-1 and Table 6-2 show the operating conditions for the particle injection.

Table 6-1. Operating conditions for nickel particle injection in pure argon (60 slpm and 500A) with argon carrier gas

<table>
<thead>
<tr>
<th>Mean size (µm)</th>
<th>Size range (µm)</th>
<th>Carrier gas (slpm)</th>
<th>Particle flow (g/min)</th>
<th>Distance from torch outlet (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>65</td>
<td>45-90</td>
<td>5.9</td>
<td>30</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 6-2. Operating conditions for nickel particle injection in the Ar-H2 mixture (54 slpm of Ar and 6 slpm H2 and 400 A) with argon carrier gas

<table>
<thead>
<tr>
<th>Mean size (µm)</th>
<th>Size range (µm)</th>
<th>Carrier gas (slpm)</th>
<th>Particle flow (g/min)</th>
<th>Distance from torch outlet (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>20-35</td>
<td>5</td>
<td>24</td>
<td>12</td>
</tr>
</tbody>
</table>

In most previous works, researchers assumed that the outlet plasma jet stream is at a steady state when coating particles are sprayed into the flow [41,48,62,76,77,86-88]. However, this assumption is invalid because it neglects the fluctuations of the plasma jet. The simulations in this work, modelled a steady state case with particle injection, and then an unsteady state case with particle injection.

For the steady state model, all of the simulation results generated from previous simulations of an unsteady state fluid flow were considered. In order to take into account the range of results, the
results were integrated in MATLAB™ and the mean mass weighted profiles were found. This approach is similar to what has been done in previous research on particle injection modeling that consider velocity and temperature are steady at torch outlet. In below equations, $V(x,y,t)$, $\rho(x,y,t)$, $h(x,y,t)$, $T_{total}$, $V(x,y)$, $\rho(x,y)$, $h(x,y)$ are respectively velocity at the torch outlet as a function of time, density at the torch outlet as a function of time, total simulation time, average velocity over time at the torch outlet, average density over time at the torch outlet, average enthalpy over time at the torch outlet. By using values of $h(x,y)$, average temperature profile, $T(x,y)$, can be extracted from mixture properties. Results are presented in next section.

\begin{align*}
V(x,y) &= \frac{1}{T_{total}} \int_{0}^{T_{total}} V(x,y,t) dt \quad \text{(6-1)} \\
\rho(x,y) &= \frac{1}{V(x,y)T_{total}} \int_{0}^{T_{total}} \rho(x,y,t)V(x,y,t)dt \quad \text{(6-2)} \\
h(x,y) &= \frac{1}{T_{total}V(x,y)\rho(x,y)} \int_{0}^{T_{total}} \rho(x,y,t)V(x,y,t)h(x,y,t) dt \quad \text{(6-3)}
\end{align*}

6.1 Plasma jet simulations for pure argon

The nickel particle feed rate was 30 g/min and the particle diameter range, mean particle diameter, and the carrier gas mass flow rate were 45-90µm, 65µm, and 5.9slpm, respectively. Figure 6-2 shows the velocity and temperature distributions of particles adopted from experimental results. Figure 6-3 and Figure 6-4 provide the velocity and temperature distribution for the steady state simulation.

Table 6-3 provides the average and standard deviation (SD) of the temperature and the velocity for the steady state results. If we compare the experimental results with those from the unsteady state simulation showed in Figure 6-5, Figure 6-6, and Table 6-4, we will notice that the unsteady state results of the particle injection in the plasma jet are in a very good agreement with experimental results. In fact, this is the final step of this study which shows how the arc fluctuations
can affect plasma at the torch outlet and, accordingly, the plasma jet and particle injection. There are two main reasons for having inaccurate results in steady state particle injection: neglecting the velocity and temperature fluctuations at the torch outlet by using the time-average profiles, and using an inaccurate and constant profile for turbulence kinetic energy production and dissipation at the torch outlet.

The temperature and velocity profiles at the torch outlet are subject to change over time. Sometimes, their fluctuations exceed more than 20% of their mean values. In this case, particles can experience different temperatures, velocities, and turbulence characteristics in the plasma jet. Therefore, it is expected that we would find a lower temperature and velocity for the particles which have wider distributions in all particle characteristics (e.g., temperature, velocity, horizontal and vertical position distribution at the substrate) due to considering the velocity and temperature fluctuations and also turbulence kinetic energy.

![Diagram](image.png)

a) Average velocity over time (m/s)  
b) Average temperature over time (K)

Figure 6-1. Contours of average velocity and temperature over time at the torch outlet

Most computational software and numerical codes use conventional functions to calculate the turbulence kinetic energy production and turbulence dissipation based on the velocity magnitude
and the outlet size. Due to high interaction and arc movement inside the torch, the turbulence kinetic energy production and turbulence dissipation are much higher in unsteady-state simulations. If we then set those profiles at the torch outlet, the particles tend to accelerate in different directions. This results in lower velocity and temperature of the particles at the substrate.

The particles' interaction with a turbulent flow was studied in these simulations. The unsteady-state particle injection model was solved and the inlet kinetic turbulence energy and energy dissipation was considered. It is clear that particle injection can affect characteristics of turbulence dramatically. The results showed that the turbulence dissipation and kinetic energy decrease dramatically (30%) in the particle region in the plasma jet.

![Figure 6-2. Experimental distribution of particle velocity and temperature measured by DPV2000 set up at 15-cm from the torch outlet](image)
Figure 6-3. Histogram of particle temperature in the steady-state simulation at 15-cm from the torch outlet

![Histogram of particle temperature in the steady-state simulation at 15-cm from the torch outlet](image1)

Figure 6-4. Histogram of particle velocity in the steady-state simulation at 15-cm from the torch outlet

![Histogram of particle velocity in the steady-state simulation at 15-cm from the torch outlet](image2)

Figure 6-5. Histogram of particle temperature in the unsteady-state simulation at 15-cm from the torch outlet

![Histogram of particle temperature in the unsteady-state simulation at 15-cm from the torch outlet](image3)
Figure 6-6. Histogram of particle velocity in the unsteady-state simulation at 15-cm from the torch outlet

Table 6-3. Mean and SD of 1800 particles for the steady-state model

<table>
<thead>
<tr>
<th></th>
<th>Velocity from experiment (m/s)</th>
<th>Velocity from numerical model (m/s)</th>
<th>Temperature from experiment (K)</th>
<th>Temperature from numerical model (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>72</td>
<td>82</td>
<td>1845</td>
<td>2041</td>
</tr>
<tr>
<td>SD</td>
<td>9.32</td>
<td>5.24</td>
<td>217.95</td>
<td>126.93</td>
</tr>
</tbody>
</table>

Table 6-4. Mean and SD of 1800 particles for the unsteady-state model

<table>
<thead>
<tr>
<th></th>
<th>Velocity from experiment (m/s)</th>
<th>Velocity from numerical model (m/s)</th>
<th>Temperature from experiment (K)</th>
<th>Temperature from numerical model (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>72</td>
<td>72.67</td>
<td>1845</td>
<td>1832.8</td>
</tr>
<tr>
<td>SD</td>
<td>9.32</td>
<td>10.95</td>
<td>217.95</td>
<td>160.1</td>
</tr>
</tbody>
</table>
Figure 6-7. Temperature of nickel particles

Figure 6-8. Velocity of nickel particles
6.2 Plasma jet simulations for argon-hydrogen mixture

This step includes particle injection modeling for argon-hydrogen mixture. The nickel particle feed rate was 24 g/min and the particle diameter range, mean particle diameter, and the carrier gas mass flow rate were 20-35 µm, 27 µm, and 3.5 slpm respectively. The experimental particle velocity and temperature distributions are shown in Figure 6-9.

Figure 6-9. Experimental distribution of particle velocity and temperature by DPV2000 set up at 12-cm from the torch outlet

The average velocity and temperature over time (integrated over time) is shown in Figure 6-10. The steady state simulation based on average velocity and temperature was simulated. Figure 6-11 and Figure 6-12 show particle velocity and temperature distributions and the summary of the results is shown in Table 6-5. Results show that the steady state particle injection simulation based on the average velocity and temperature over time has higher particle temperature and velocity and also larger standard deviation.

Table 6-5. Mean and SD of 1800 particles for the steady-state model at 12-cm from the torch outlet

<table>
<thead>
<tr>
<th></th>
<th>Velocity from experiment (m/s)</th>
<th>Velocity from numerical model (m/s)</th>
<th>Temperature from experiment (K)</th>
<th>Temperature from numerical model (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>119</td>
<td>130</td>
<td>2676</td>
<td>2820</td>
</tr>
<tr>
<td>SD</td>
<td>17.32</td>
<td>8.29</td>
<td>89.57</td>
<td>64.10</td>
</tr>
</tbody>
</table>
Unsteady model was created based on the velocity, temperature, and turbulent characteristics over time of flow exiting the torch. Figure 6-13, Figure 6-14, and Table 6-6 present the velocity and temperature distribution for unsteady particle injection simulation.

Figure 6-10. Contours of average velocity and temperature over time at the torch outlet

Figure 6-11. Histogram of temperature of particles in steady-state simulation at 12-cm from the torch outlet
Figure 6-12. Histogram of velocity of particles in steady-state simulation at 12-cm from the torch outlet

Figure 6-13. Histogram of temperature of particles in unsteady simulation at 12-cm from the torch outlet

Figure 6-14. Histogram of velocity of particles in unsteady simulation at 12-cm from the torch outlet

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The unsteady results are in a very good agreement with experimental results. In fact, results show that the temperature and velocity fluctuations can affect the particle acceleration and heating. As we mentioned before, considering the velocity and temperature fluctuations and also the turbulence kinetic energy production the torch outlet produces relatively accurate results for particle injection.

When the velocity and temperature of the torch outlet is considered as steady-state, particle velocity and temperature have lower standard deviation and higher mean values. Therefore, velocity fluctuation can reduce the particle velocity and causes the more uniform particle heating. As a result, constant temperature and velocity profile at the torch outlet can cause over estimate of the particle velocity and temperature.
Simulating a case of fluid flow with computational fluid dynamics (CFD) generally requires solving Navier–Stokes partial differential equations (PDE), namely conservation of momentum, and conservation of mass (continuity) in all main coordination directions x, y, z. In order to find temperature changes across the fluid flow, enthalpy (energy) equations are added to these sets of PDEs and solved over each node. If the fluid flow is a turbulent fluid flow, a turbulent model must be selected and coupled into the PDEs.

Navier-Stokes PDEs are a set of equation systems that describe the motion of a viscous fluid. These equations are of the form described in equation 7-1 [66,67]:

\[
\frac{\partial}{\partial t}(\rho \Phi) + \text{div}(\rho \vec{u} \Phi) = \text{div}(\Gamma_{\Phi} \text{grad} \Phi) + S_{\Phi}
\]

where \( \Phi \) is a conservative independent variable. The first term (transient term) of the above equation shows the changes of parameter \( \Phi \) with time. This term is zero in a steady flow. The second term of this equation represents the motion of fluid (of velocity \( \vec{u} \)). \( \text{div}(\Gamma_{\Phi} \text{grad} \Phi) \) represents the fluid transfer due to diffusion (both molecular diffusion and turbulent diffusion) and \( \Gamma_{\Phi} \) is the effective diffusion coefficient. The source term \( S_{\Phi} \) represents the generation or degeneration of parameter \( \Phi \). For example, when the conservative variable \( \Phi \) is enthalpy, \( S_{\Phi} \) could be a source of thermal energy in the system.

In a turbulent fluid flow, viscosity (\( \mu \)) needs to be replaced by the effective turbulent viscosity (\( \mu_{eff} = \mu + \mu_t \)), which is a function of the fluid flow velocity where \( \mu_t \) is turbulent viscosity. The dependency of \( \mu_t \) to velocity is defined differently in every turbulent model. In each of these models, \( \mu_t \) is calculated using a set of equations that relate the kinetic energy of the turbulent flow to the rate of kinetic energy dissipation [66,68].
7.1 $k - \varepsilon$ Model

In the $k - \varepsilon$ turbulent model, the kinetic energy of the fluid flow ($k$) is correlated to the rate of kinetic energy dissipation in the flow ($\varepsilon$). In this model, we assume that the fluid flow is fully turbulent and that the molecular viscosity effects are negligible.

The following transfer equations describe how the kinetic energy of the fluid flow ($k$) is correlated to the rate of kinetic energy dissipation in the fluid flow ($\varepsilon$).

\[
\frac{D(\rho k)}{\partial t} = \frac{\partial}{\partial x_i} \left[ \frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x_i} \right] + G_k + B - \rho \varepsilon \quad 7-2
\]

\[
\frac{D(\rho \varepsilon)}{\partial t} = \frac{\partial}{\partial x_i} \left[ \frac{\mu_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_i} \right] + C_{1\varepsilon} G_k \frac{\varepsilon}{k} + C_{1\varepsilon}(1 - C_3) \frac{\varepsilon}{k} B - C_{2\varepsilon} \rho \varepsilon \frac{\varepsilon^2}{k} \quad 7-3
\]

\[
\mu_t = C_\mu \frac{k^2}{\varepsilon} \quad 7-4
\]

where $G_k$ represents the turbulent kinetic energy generation due to gradients of average velocity. $B$ represents the effects of buoyancy forces and is calculated as explained below. $C_\mu = 0.09, C_{1\varepsilon} = 1.44,$ and $C_{2\varepsilon} = 1.92$ are constants. $\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.3$ represent turbulent Prandtl numbers for $k$ and $\varepsilon$, respectively [69].

7.2 $k - \omega$ Model

$k - \omega$ model was developed to simulate mixing layers and various jet flows. It is a strong model to simulate flows with low Re number (transient Re numbers).

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_i} \left[ \left( \mu_t + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G_k - Y_k + S_k \quad 7-5
\]
\[
\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho \omega u_i) = \frac{\partial}{\partial x_i} \left[ \left( \mu_t + \frac{\mu_t}{\sigma_\omega} \right) \frac{\partial \omega}{\partial x_i} \right] + G_\omega - Y_\omega + S_\omega \tag{7-6}
\]

\[
\mu_t = \rho \frac{k}{\omega} \tag{7-7}
\]

where \( \omega \) is specific dissipation rate, \( G_k \) is the generation of turbulent kinetic energy due to mean velocity gradients, \( G_\omega \) is generation of \( \omega \), \( Y_k \) and \( Y_\omega \) are dissipation of \( k \) and \( \omega \) due to turbulence. \( \alpha_k \) and \( \alpha_\omega \) are turbulent Prandtl numbers (equal to 2) and \( S_k \) and \( S_\omega \) are source terms, which are zero in this model [69].

### 7.3 LES Model

The operation sequence in a conventional thermal plasma torch is that first, the gas is injected and ionized to a plasma state. Due to presence of high temperature and low-temperature zones in a thermal plasma torch, multi-scale vortices form. The low temperature fluid has a low kinematic viscosity and high local Reynolds number. This zone contains multi-scale eddies the size of a few tens of micrometer. On the other hand, the high temperature fluid, with high kinematic viscosity and low local Reynolds number contains large eddies the size of a few millimeters. When the low-temperature flow (containing small eddies) enters the high-temperature plasma in the torch (containing larger eddies), the small eddies suppress the turbulence in the fluid. This process is called laminarization.

It is very challenging to correctly simulate a thermal plasma fluid flow inside the torch due to the presence of phenomena like laminarization. The turbulence model used for the simulation should be capable of capturing processes and phenomena like laminarization.

The \( k - \varepsilon \) model has been widely used for thermal plasma simulation. It should be noted that this method is based on the assumption that the eddy scales of turbulent kinetic energy, and energy dissipation are apart from one another. This assumption is not valid in a region with low Reynolds number. Therefore, many researchers (e.g., Shiegeta et al.[64]) used a large-eddy simulation (LES)
approach to simulate the plasma jet stream and the dynamic motions of the multi-scale vortices inside the flow.

In order to correctly model the multi-scale eddies in this density varying plasma stream, the large grid structures (GS) and the small sub-grid scale should be separated. Shigeta et al. used a Favre-filtering operation to break down these and derive the following governing equations:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \tag{7-8}
\]

\[
\frac{\partial (\rho \vec{u})}{\partial t} + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla P + \nabla \cdot \vec{\tau}^{GS} \nabla \cdot \vec{\tau}^{SGS} + \frac{\mu_0}{2} \sigma \text{Real}(\vec{E} \times \vec{H}^\prime) \tag{7-9}
\]

Where \(\vec{\tau}^{GS}\) and \(\vec{\tau}^{SGS}\) represents diffusions at the resolved grid structures and at the sub-grid scale, respectively. \(\frac{\mu_0}{2} \sigma \text{Real}(\vec{E} \times \vec{H}^\prime)\) represents the effective value of the Lorentz force caused by the induced electromagnetic field, where \(\vec{H}^\prime\) represents complex conjugate of magnetic field.

\[
\frac{\partial (\rho \vec{h})}{\partial t} + \nabla \cdot (\rho \vec{u} \vec{h}) = -\nabla \cdot \vec{q}^{GS} - \nabla \cdot \vec{q}^{SGS} + \frac{1}{2} \sigma \vec{E} \cdot \vec{E} - R + \vec{S} : \vec{\tau}^{GS} + \vec{\varepsilon}^{SGS} \tag{7-10}
\]

\[
\vec{\tau}^{GS} = \eta [2\vec{S} - \frac{2}{3} (\nabla \cdot \vec{u}) \vec{I}] \tag{7-11}
\]

where \(\frac{\partial (\rho \vec{h})}{\partial t}\) represents thermal conduction at the resolved grid structures, and \(\nabla \cdot (\rho \vec{u} \vec{h})\) represents the apparent thermal diffusion attributable to turbulent eddies at the sub-grid scale. \(\frac{1}{2} \sigma \vec{E} \cdot \vec{E}\) denotes the heat generation caused by the electric field at the grid structures and the sub-grid scale. In a plasma fluid flow, the effects of Joule heating and radiation losses are dominant. \(R, \vec{I}, \vec{\tau}, \vec{S},\) and \(\vec{q}\) are radiative heat loss, unit matrix, traceless stress tensor, velocity strain tensor, and heat flux vector respectively.
7.3.1 The sub-grid scale model

Relying on the concept of eddy viscosity, the quantities at the sub-grid scale are determined. The following governing equations are derived using the Smagorinsky-type model [89] at the resolved grid structures:

$$\tau_{SGS}^C = -\rho C \bar{\Delta}^2 D (2\bar{S}^C - \frac{2}{3} (\nabla \cdot \vec{u}) \bar{T})$$  \hspace{1cm} 7-12

$$\bar{q}_{SGS}^C = -\frac{\rho C \bar{\Delta}^2 D}{Pr_T} \nabla h$$  \hspace{1cm} 7-13

$$\varepsilon_{SGS} = \rho C \bar{\Delta}^2 D [2(\bar{S}:\bar{S}) - \frac{2}{3} (\nabla \cdot \vec{u})^2]$$  \hspace{1cm} 7-14

where $\bar{\Delta}$ is the filter width equal to $\bar{\Delta} = V_{CV}^{1/3}$ $V_{CV}$ is the volume of each control volume. And $D$ is equal to $D = \sqrt{2(\bar{S}:\bar{S})}$. And $Pr_T$ is turbulent Prandtl number.

Smagorinsky model (as shown in equations above) has parameter $C$ which is a constant [89]. Therefore, this model can correctly simulate the multi-scale eddies in turbulent and laminar regions of the fluid flow inside the torch. Moreover, it is incapable of capturing the turbulence suppression under high-viscosity conditions. In their study, Shigeta et al. choose to locally define the model parameter $C$ using a coherent structure model [64].

7.4 Results

An SG-100 torch was modeled. Model was solved for three different turbulence model, $k - \varepsilon$, $k - \omega$, and LES. The operating conditions an argon-hydrogen mixture (54 slpm argon and 6 slpm hydrogen) and 400 A.

Figure 7-1 and Figure 7-2 show temperature and velocity contours in X-Z plane, respectively. Results demonstrate that $k - \omega$ model, as expected, simulates a higher peak for velocity and temperature. This is because $k - \omega$ turbulence model does not encounter the tendency of fluid to
mixing. This means that the model predicts lower mixing of high temperature fluid with low-
temperature fluid, which results in higher peak in temperature and velocity.

The $k - \varepsilon$ model is based on the assumption that turbulence is isotropic. This model is used for
fully turbulent flows. This means that this model shows high rate of mixing, so the mixing of high-
temperature and low-temperature fluid is overestimated. Therefore, this model simulates lower
peak in velocity and temperature.

LES model is a turbulent model best suited for a fluid flowing through laminar and turbulent zones.
This model simulates results close to $k - \varepsilon$ model. However, the model considers lower level of
mixing.

Figure 7-3 and Figure 7-4 shows velocity and temperature contours at torch outlet. As expected,
temperature and velocity profile, derived from $k - \varepsilon$ model, are more uniform compared to $k - \omega$
results, which show higher fluctuations. The results from LES model simulation are close to the ones from $k - \varepsilon$ simulations.
Figure 7-2. Velocity contours on x-z plane for different turbulence models

Figure 7-3. Velocity contours at the torch outlet at t=1120 μs for different turbulence models
Velocity and temperature profiles are shown in Figure 7-5 and Figure 7-6. The peak of temperature and velocity in $k - \omega$ simulations are higher than the peak of temperature and velocity in $k - \varepsilon$ and LES simulations. Results show that $k - \omega$ model shows lower mixing compared to $k - \varepsilon$ and LES models.

As mentioned earlier, $k - \varepsilon$ model is derived for fully turbulent flows. There are debates over whether $k - \varepsilon$ model can be used for transient flows (most of plasma models where $2000 < Re < 10000$). Researchers showed that LES model is capable of simulating transient flows as well as fluid flows containing both laminar and turbulent zones. LES model results are comparable to ones driven from the simple and practical $k - \varepsilon$ model. Based on these similar results, we conclude that using $k - \varepsilon$ model for modeling the jet stream in plasma torches is appropriate. Moreover, our assumption of considering the plasma stream fully turbulent and isotropic is a valid assumption.
Figure 7-5. Temperature profile at the torch outlet at t=1120 μs for different turbulence models.

Figure 7-6. Velocity profile at the torch outlet at t=1120 μs for different turbulence models.
Figure 7-7 and Figure 7-8 show average velocity and average temperature at torch outlet. The results from k-ε model simulations are less prone to change due to arc fluctuations. This is because $k - \varepsilon$ model has higher mixing. The results show higher peak in velocity and lower minimum velocity in $k - \omega$ model. In $k - \varepsilon$ and LES models, the fluid experiences higher mixing rate, which will result in a more stable plasma jet stream at torch outlet.

Our results (see Figure 7-9 and Figure 7-10) show that the results from $k - \omega$, $k - \varepsilon$ and LES models are comparable to one another. Due to the fact that $k - \varepsilon$ model encounters higher mixing of the fluid inside the torch, $k - \omega$ results show a 6% higher peak in velocity, and 2 to 3% higher peak in temperature compared to the one predicted by $k - \varepsilon$ and LES models. On the other hand, LES and $k - \varepsilon$ model results are in good agreement with one another.
Figure 7-8. Average temperature at the torch outlet over time for different turbulence models

Figure 7-9. Velocity at the centerline at the torch outlet over time for different turbulence models
Figure 7-10. Temperature at the centerline at the torch outlet over time for different turbulence models

Kinetic energy is used to calculate particles velocity fluctuations in Random Walk Model, a standard boundary condition for turbulence kinetic energy is calculated based on below equation where I is turbulence intensity.

\[ k = \frac{3}{2} (uI)^2 \]  

Many plasma jet models have used this equation to calculate the turbulence kinetic energy at the boundary conditions (e.g. [41,48,62,77,86,88]). Figure 7-11 and Figure 7-12 show the boundary condition for turbulence kinetic energy for plasma jet in conventional numerical models compare to our simulation which uses the results from the simulation. Results show using conventional boundary conditions for calculating turbulence kinetic energy at the inlet may not result a good estimation. So, it can affect the particle injection simulation.
a) Estimated turbulence kinetic energy based on mean of velocity over time (conventional B.C.)

b) Turbulence kinetic energy from unsteady simulation at $t=520 \mu s$

Figure 7-11. Contours of turbulence kinetic energy for argon plasma at the plasma jet discharge surface in conventional research work(a) and in this study(b)

a) Estimated turbulence kinetic energy based on mean of velocity over time (conventional B.C.)

b) Turbulence kinetic energy from unsteady simulation at $t=1020 \mu s$

Figure 7-12. Contours of turbulence kinetic energy for argon-hydrogen plasma at the plasma jet discharge surface in conventional research work(a) and in this study(b)
Chapter 8
Conclusion and suggestions for future work

8 Conclusion and suggestions for future work

8.1 Summary and Conclusions

In this research, we aimed to produce a comprehensive study of a DC plasma torch. As explained in details in Chapter 1, an electric arc initiated from the anode of the torch and randomly strikes the cathode (wall) of the torch. This electric current heats and partially ionizes the gas streaming through the torch and produces plasma (ionized gas) jet. The extremely hot gas stream is directed towards the torch outlet where coating powder particles are injected into the ionized gas. The coating powder particles are subsequently melted, accelerated and directed at the substrate. To produce a high quality coating, the powder particles should be uniformly heated and accelerated before deposition onto the substrate. In other words, the ability to create a high quality and uniform coating is highly reliant on the torch’s ability to generate a flow of particles with consistent particle temperature and velocity at the point of impact. Assuming that the powder injection is controlled adequately, the consistency of the heating and acceleration of the powders depends to the steadiness of the plasma jet. The jet’s steadiness is dictated by the arc fluctuations within the torch. Plasma arcs exhibit strong voltage fluctuations due to movement of the anode arc root attachment. Understanding the arc movement within the torch, and how it affects the flow and temperature fields of the plasma jet exiting the torch, is therefore of great importance. There are numerous research works that studied a few parameters of this problem under specific assumptions. However, never before, has there been an attempt on producing a comprehensive three dimensional model that simulates the plasma jet stream inside the torch using voltage fluctuations. The present study aimed to develop such an inclusive model incorporating thermal efficiency and voltage fluctuations from experiment results.

A detailed three dimensional model of the plasma torch was developed. A user defined FLUENT code was developed in which the general fluid mechanics governing equations were modified to incorporate terms representing electromagnetics equations.
The research of current study was of a hierarchical nature. Therefore, multiple series of simulations needed to be run in order to get to the final simulation cases. First, experiments were done to find the efficiency, voltage fluctuations, and power of the torch. Then, a series of steady state simulations were run to find the voltage drop and efficiency over a range of arc radii and arc lengths. Overlaying the experimental and simulation results the most possible case of arc root attachment point was identified and added to the simulation model.

The second step of the project was to simulate the unsteady plasma jet stream inside the flow. A series of simulations were run to produce unsteady simulation results, and thus voltage drop and efficiency, when the arc root attachment point is set based on steady-state results. The results of simulations were studied and the result over the outlet cross section was selected as a representative of torch outlet in further simulations.

Third, the plasma jet was simulated using the boundary condition adopted from prior simulations. A new module was added to the model that simulated the injection of the coating particles and their heating and acceleration through their journey inside the plasma jet stream to the substrate. A second set of simulations were run which used unsteady simulation results (from prior steps) as initial condition.

Finally, the model was used to simulate the plasma jet stream composed of various common plasma torch gas mixtures (e.g., Ar + H₂, Ar + CO₂ + CH₄) inside the Blue torch.

The result of voltage fluctuations show a very good correlation with measurements. In the present work, the coefficient of determination (R²) is 0.982. So, the model was created is both thermally and electrically matched with experiment.

Voltage drop increases as the arc length increases and decreases when the arc radius increases. When arc length is longer, the average voltage drop is larger and as expected, increasing the arc length increases the arc power because the electric current remains constant.

In argon and argon–hydrogen plasma, temperature is close to 30 kK at the cathode where the heat generation is maximum. As arc fluctuates, the temperature fluctuates at the torch outlet. This high fluctuation (15% for pure argon and 20% for argon-hydrogen) can change the particle heating conditions.
Arc fluctuation causes the velocity fluctuation at the torch outlet. The velocity at the torch outlet fluctuates 25% in argon plasma and 30% in argon-hydrogen plasma. It causes the particles experiencing different gas velocities. Velocity is more sensitive than temperature to arc fluctuations. The maximum velocity occurs close to the torch outlet.

Turbulence generation is highly dependent on velocity gradient. Turbulence kinetic energy generation is one of the main factors affecting particle acceleration and heating. When the arc fluctuates, the velocity gradient is higher. So it should be taken into account to calculate the particle heating.

Argon-hydrogen plasma is a better conductor of heat compared to argon plasma torch. The temperature and velocity profiles are more evenly distributed compared to those of the plasma medium constituted of pure argon. The reason for this is that hydrogen molecules are much smaller than argon molecule and their movements are fast. Therefore, their heat transfer coefficient is much higher than that of argon.

Blue torch is a new torch which is designed in CACT. Results show although the voltage fluctuation is higher, the velocity and temperature fluctuations at the torch outlet are lower due to the more effective mixing of high and low temperature zones. The velocity fluctuation is less than 10% and the temperature fluctuation is 2%. Blue torch is longer compared to SG-100 torch it causes a large drop in the thermal energy within the torch resulting in lower efficiency.

In most previous works, researchers assumed that the outlet plasma jet stream is at a steady state when coating particles are sprayed into the flow. However, this assumption is invalid because it neglects the fluctuations of the plasma jet. The simulations in this work, modelled a steady state case with particle injection, and then an unsteady state case with particle injection. Results show that when the arc fluctuates the particle temperature and velocity is completely matched with those from experiment.

Most computational software and numerical codes use conventional functions to calculate the turbulence kinetic energy production and turbulence dissipation based on the velocity magnitude and the outlet size. Due to high interaction and arc movement inside the torch, the turbulence kinetic energy production and turbulence dissipation are much higher in unsteady state simulations. If we then set those profiles at the torch outlet, the particles tend to accelerate in
different directions. This results in lower velocity and temperature of the particles at the substrate. When the velocity and temperature of the torch outlet is considered as steady-state, particle velocity and temperature have lower standard deviation and higher values. Therefore, velocity fluctuation can reduce the particle velocity. As a result, constant temperature and velocity profile at the torch outlet can cause over estimate of the particle velocity and temperature.

8.2 Suggestions for future work

As explained earlier, the present research focused on a comprehensive study of the phenomena occurring inside a plasma torch chamber. The boundaries – including the anode, the walls and their interaction with the fluid – were entered in this study as rather simplified boundary conditions. Future research in this area could improve upon these simulations by modeling the heat transfer and electromagnetic mechanisms (e.g., ion recombination, anode fall, electron condensation) on the walls and boundaries.

Alaya et al. added cathode to the simulation domain replacing the boundary condition that represents cathode [44]. With the rapid progress in computation speed and cost, it will be possible to add anode to the simulation domain as well and replace anode boundary conditions. This will be step further towards the most accurate results one could get from computational simulations.

The results of the present research pave the way for redesigning plasma torches and optimizing their features (e.g., cathode and anode configurations, particle sprinkles) to achieve better performance and higher quality coating. The optimized design could be geared towards implementing new technologies in the torch to achieve superior results. Boosting the power of the arc and thermal efficiency of the torch [1] and increasing the intensification of the energy exchange between the gas flow and the electric arc are only a couple of commonly desired improvements. In addition, an efficient cooling system that removes excess heat and prevents further deterioration of the torch has been the target of many recent research investigations.

A closer look at momentum equations in turbulence flow reveals that the time averaging momentum equations may be sensitive to magnetic and electric fields’ fluctuations. In other words, magnetic and electric fields may produce extra term in time averaging momentum equation. It is the author’s suggestion that the effect of these fluctuations on MHD equations be investigated.
The results of this research could be used as a starting point for simulating the particles, their physical state, temperature and velocity at any given point, and their impact with the substrate. A multiphase model should be developed (e.g., VOF) that simulates the transformation of solid particles into pasty, and then liquid, droplets while recording their dynamics. Such an accurate model could be used to control and optimize the coating being adhered on the substrate.
References


A. Material properties

The material properties of the fluid inside the torch is shown in figures below. The properties for argon, argon-hydrogen, and CO$_2$-based mixtures were taken from different sources [1,3,36,72-74].

A.1. Argon properties

Figure A-1. Specific heat of argon
Figure A-2. Thermal conductivity of argon

Figure A-3. Viscosity of argon
Figure A-4. Electrical conductivity of argon

Figure A-5. Emissivity of argon
A.2. Argon-Hydrogen Properties (10% volumetric H2 and 90% volumetric Ar)

Figure A-6. Emissivity of argon-hydrogen mixture (10% volumetric H2 and 90% volumetric Ar)

Figure A-7. Specific heat of argon-hydrogen mixture (10% volumetric H2 and 90% volumetric Ar)
Figure A-8. Viscosity of argon-hydrogen mixture (10% volumetric H2 and 90% volumetric Ar)

Figure A-9. Electrical conductivity of argon-hydrogen mixture (10% volumetric H2 and 90% volumetric Ar)
A.3. \( \text{CO}_2 \) based mixture properties (41.1% volumetric \( \text{CO}_2 \), 47.1% volumetric \( \text{Ar} \), and 11.8% volumetric \( \text{CH}_4 \))

Figure A-10. Thermal conductivity of argon-hydrogen mixture (10% volumetric H2 and 90% volumetric \( \text{Ar} \))

Figure A-11. Specific heat of argon-hydrogen mixture (41.1% volumetric \( \text{CO}_2 \), 47.1% volumetric \( \text{Ar} \), and 11.8% volumetric \( \text{CH}_4 \))
Figure A-12. Thermal conductivity of argon-hydrogen mixture (41.1% volumetric CO₂, 47.1% volumetric Ar, and 11.8% volumetric CH₄)

Figure A-13. Viscosity of argon-hydrogen mixture (41.1% volumetric CO₂, 47.1% volumetric Ar, and 11.8% volumetric CH₄)
Figure A-14. Electrical conductivity of argon-hydrogen mixture (41.1% volumetric CO2, 47.1% volumetric Ar, and 11.8% volumetric CH₄)
B. FLUENT UDF

The UDF code is available in Table A-1.

Table A-1. FLUENT UDF code

```c
#include "udf.h"
#include "sg.h"
#include "mem.h"
real mu0=4.*3.1415e-7;

UDF for defining user-defined scalars and their gradients

#include "udf.h"
DEFINE_ADJUST(final,d)
{
    Thread *t;
    cell_t c;

    thread_loop_c(t,d)
    {
        begin_c_loop(c,t){
            C_UDMI(c,t,0) = -C_UDSI_G(c,t,0)[0]; /*Ex*/
            C_UDMI(c,t,1) = -C_UDSI_G(c,t,0)[1]; /*Ey*/
            C_UDMI(c,t,2) = -C_UDSI_G(c,t,0)[2]; /*Ez*/
            C_UDMI(c,t,3) = NV_MAG(C_UDSI_G(c,t,0)); /*E*/
            C_UDMI(c,t,4) = C_UDSI_DIFF(c,t,0)*C_UDMI(c,t,0); /*jx*/
            C_UDMI(c,t,5) = C_UDSI_DIFF(c,t,0)*C_UDMI(c,t,1); /*jy*/
            C_UDMI(c,t,6) = C_UDSI_DIFF(c,t,0)*C_UDMI(c,t,2); /*jz*/
            C_UDMI(c,t,7) = C_UDSI_DIFF(c,t,0)*C_UDMI(c,t,3); /*j*/
            C_UDMI(c,t,8) = C_UDSI_G(c,t,3)[1]-C_UDSI_G(c,t,2)[2]; /*Bx=Az/y-Ay/z */
            C_UDMI(c,t,9) = C_UDSI_G(c,t,1)[2]-C_UDSI_G(c,t,3)[0]; /*By=Ax/z-Az/x */
            C_UDMI(c,t,10) = C_UDSI_G(c,t,2)[0]-C_UDSI_G(c,t,1)[1]; /*Bz=Ay/x-Ax/y */
            C_UDMI(c,t,11) = sqrt(pow(C_UDMI(c,t,8),2.0)+pow(C_UDMI(c,t,9),2.0)+pow(C_UDMI(c,t,10),2.0)); /*B*/
            C_UDMI(c,t,12) = (C_UDMI(c,t,5)*C_UDMI(c,t,10)-C_UDMI(c,t,6)*C_UDMI(c,t,9)); /*Fx=jyBz-jzBy */
            C_UDMI(c,t,13) = (C_UDMI(c,t,6)*C_UDMI(c,t,8)-C_UDMI(c,t,4)*C_UDMI(c,t,10)); /*Fx=jyBx-jzBy */
            C_UDMI(c,t,14) = (C_UDMI(c,t,4)*C_UDMI(c,t,9)-C_UDMI(c,t,5)*C_UDMI(c,t,8)); /*Fz=jxBy-jyBx */
            C_UDMI(c,t,19) = C_UDMI(c,t,14); /**/
        }
    }
}
```

C_UDMI(c,t,15) = sqrt(pow(C_UDMI(c,t,12),2.0)+pow(C_UDMI(c,t,13),2.0)+pow(C_UDMI(c,t,14),2.0)); /* F */

C_UDMI(c,t,16)=C_UDMI(c,t,3)*C_UDMI(c,t,3)*C_UDSI_DIFF(c,t,0); /* energy Joul=E*j */
C_UDMI(c,t,18)=C_UDMI(c,t,16);

For 0.9% Ar and 10 % H2 */
}
end_c_loop(c,t)
}
}

#define SOURCE(x_mom_source,c,t,dS,eqn)
{
    real source;
    source =1.0*C_UDMI(c,t,12);
    dS[eqn] = 0.0;
    return source;
}

#define SOURCE(x_mom_half,c,t,dS,eqn)
{
    real source;
    source =C_UDMI(c,t,12);
    dS[eqn] = 0.0;
    return source;
}

#define SOURCE(y_mom_source,c,t,dS,eqn)
{
    real source;
    source = 1.0*C_UDMI(c,t,13);
    dS[eqn] = 0.0;
    return source;
}

#define SOURCE(y_mom_half,c,t,dS,eqn)
{
    real source;
    source = C_UDMI(c,t,13);
    dS[eqn] = 0.0;
    return source;
DEFINE_SOURCE(z_mom_source,c,t,dS,eqn)
{
  real source;
  source = 1.0*C_UDMI(c,t,14);
  dS[eqn] = 0.0;
  return source;
}

DEFINE_SOURCE(z_mom_half,c,t,dS,eqn)
{
  real source;
  source = C_UDMI(c,t,14);
  dS[eqn] = 0.0;
  return source;
}

DEFINE_SOURCE(energy_Joul_125,c,t,dS,eqn)
{
  real source;
  source = C_UDMI(c,t,16);
  dS[eqn] = 0.0;
  return source;
}

DEFINE_SOURCE(energy_Joul,c,t,dS,eqn)
{
  real source;
  source = C_UDMI(c,t,18);
  dS[eqn] = 0.0;
  return source;
}

DEFINE_SOURCE(energy_radiation,c,t,dS,eqn)
{
  real source;
  source = C_UDMI(c,t,17);
  dS[eqn] = 0.0;
  return source;
}
/* Ax Source term*/
DEFINE_SOURCE(x_potential_Vector,c,t,dS,eqn)
{
real source;
source = 4.0*(3.1415e-7)*C_UDMI(c,t,4); /* jx */
dS[eqn] = 0.0;
return source;
}

/************************************************/
/* Ay Source term*/
DEFINE_SOURCE(y_potential_Vector,c,t,dS,eqn)
{
real source;
source = 4.0*(3.1415e-7)*C_UDMI(c,t,5); /* jy */
dS[eqn] = 0.0;
return source;
}

/************************************************/
/* Az Source term*/
DEFINE_SOURCE(z_potential_Vector,c,t,dS,eqn)
{
real source;
source = 4.0*(3.1415e-7)*C_UDMI(c,t,6); /* jz */
dS[eqn] = 0.0;
return source;
}

/************************************************/
DEFINE_PROFILE(cathod_temperatur_profile,tf,i)
{
real x[ND_ND];
real r;
real rc=9.1e-4;
face_t f;
begin_f_loop(f,tf)
{
if PRINCIPAL_FACE_P(f,tf)
{
F_CENTROID(x,f,tf);
r = x[0]*x[0]+x[1]*x[1];
F_PROFILE(f,t,f,i) = 300.+3200.*exp(-(r*r)/(rc*rc*rc*rc)); } }
end_f_loop(f,tf)