

Article

Analytical Study of Velocity Field Development in the Constrictor of a 200 kW Arc Jet

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Abstract

The following research focuses on the study of the behavior of air plasma developed inside a 200 kW arc-jet constrictor. The scope of the analysis performed in the present document is focused specifically on the velocity fields and their characteristics inside the constrictor domain. Among them, the velocity magnitude, the distribution of the radial profiles at different stations along the length of the constrictor, and the axial velocity profile distribution. The analytical study considers mathematical models, which include air properties like specific heat, thermal conductivity, electric conductivity and enthalpy. The axial enthalpy distribution is shown at different radii of the constrictor in order to explain the presence of the velocity fields inside the control volume of interest. In the present work, it was found that the magnitude of the air plasma velocity fields increases due to the contact with the electric arc along the constrictor, reaching maximum velocity values of 5000 m/s at 10,000 K in the center of the constrictor and gradually decreasing when the constrictor radius approaches the wall. These findings provide insight into performance aspects of an arc jet constrictor using atmospheric air as a propellant. A key limitation of the present study stems from the initial assumptions and restrictions detailed in the Materials and Methods section. These constraints inherently alter several plasma flow parameters, namely the Lorentz force, the radial variation of the electric potential, etc.

Keywords: arc jet; velocity; enthalpy; profile



Academic Editor: Nikolay Yu. Peskov

Received: 7 May 2026

Revised: 23 June 2026

Accepted: 30 June 2026

Published: 23 July 2026

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1. Introduction

Related to the application of electro-thermal propulsion, arc jets can be used in different space missions; such applications find an opportunity in a variety of devices or apparatus as deep space probes, satellites and others. The kind of propellant used for this purpose can be of different types: Hydrazine, Argon, Nitrogen, Xenon, among others. This document focuses on the use of atmospheric air as a propellant. Due to the abundance of this gas found in the atmosphere of the planet Earth, recent studies have been performed related to the Atmospheric Breathing Electric Propulsion (ABEP), these studies focus on the evaluation of technology that could have an impact on the operational costs of a specific space mission using a device like the one analyzed in this document. The effects—in terms of a space mission's operational costs—would be significant, according to Zheng et al. [1],

who consider the feasibility of using ABEP devices to achieve the purpose mentioned before. Electro-thermal propulsion devices generate significant magnitudes of thrust at certain scales. It varies depending on the propellant used. This kind of electric propulsion is divided into two categories: the first one operates by the use of electric arcs, the second one by the use of microwaves. Several research documents from different organizations have been published allowing the analysis of experimental or analytical results compared with data shared from documents such as technical reports, theses, and papers. An important part of this research was developed in the second half of the twentieth century. Some aerospace companies and agencies such as AVCO, GSC, Primex, IRS, Aerojet, and NASA, developed commercial arc jets for space mission applications, according to Wollenhaupt et al. [2], using a variety of propellants at different power values.

Different studies have been performed over many years related to the performance of the arc-jet thrusters, the nature of electric arcs, the dynamics of the interactions between the electric arcs, and different propellants. The variables affected in this process, such as enthalpy, temperature, velocity fields, thermal conduction, and electrical conduction, are research topics of significant interest to space propulsion purposes. Many authors have studied this kind of thermoelectric propulsion device and the phenomena involved in these processes. For example, King [3] developed a model analyzing the interaction between an electric arc and a specific propellant inside a duct; in this case, nitrogen and air were used as propellants. The main focus of this work is on the diffusion of the arc at low currents, and the behavior of the arc central core at high power. Other authors, such as Goldenberg [4], developed an approximation method involving the Elenbaas differential equation in order to compute the radial temperature profile in the column of an electric arc, including thermal and electrical conductivity properties. Hansen [5], for his part, studied different aspects related to arc jets from the thermodynamic point of view. These included the consideration of compressibility, energy, entropy, specific heat, speed of sound, coefficients of viscosity, thermal conductivity, and Prandtl numbers of different gases (in a temperature range from 500 K to 15,000 K). Among the authors working on arc-jet topics such as performance, operational conditions and aspects related to plasma behavior inside the arc-jet domain, Stine & Watson [6] studied a model that provides an approximation for the internal distribution of specific enthalpy, and thermal and electrical conductivity in any zone of the constrictor domain. Bauer [7,8] studied the behavior of air when heated to temperatures in ranges from 1000 K to 10,000 K. The studies performed by this author focus on the behavior of air at elevated temperatures. Initially, air acts as a neutral gas mixture consisting primarily of nitrogen, oxygen, and noble gases like argon and xenon. As the temperature rises, these constituents undergo a dissociation process. If the temperature surpasses 2000 K, thermal ionization begins to occur. In related research, Yamada et al. [9] investigated the characteristics of electric arcs using a cross-flow arc (CFA) model. Their work simulated an arc column to analyze arc deformation within a constrictor domain. Finally, determining the temperature distribution inside the arc jet required evaluating both the mass transport properties and thermal diffusivity of the propellants.

Although previous experimental and analytical studies investigated thermodynamic properties and enthalpy distributions in arc jet thrusters [10,11], detailed analytical characterization of the velocity profile development inside high-power arc-jet constrictors remains limited. The novelty of the present work lies in extending the Stine & Watson [6] analytical framework to examine the axial evolution of enthalpy profiles within a 200 kW arc-jet constrictor operating with atmospheric air. The proposed analysis provides a spatial description of the axial and radial velocity fields at different axial constrictor stations and radii, offering additional insight into the internal plasma-flow behavior prior to expansion through the nozzle.

2. Materials and Methods

The present analytical method focuses on the velocity behavior of the air-based plasma and considers the Stine & Watson model [6] and the Cengel et al. [12] method as a basis for predicting the enthalpy distribution within the constrictor and velocity magnitudes of a 200 kW arc jet. Compared to other models, such as core-flow, and the uniformly heated propellant mentioned by Wallner et al. [13], the Stine & Watson model [6] analyzes the axial convection heat transfer and specific enthalpy gradient terms.

The first approach to be considered in the present analysis would be the dimension characteristics of the 200 kW arc jet constrictor. According to Stine & Watson [6], the restrictions and air plasma characteristics established for this study are as follows:

- The airflow is assumed to be one-dimensional, laminar, steady-state, and with a constant mass flow rate;
- The electric discharge is steady;
- Heat loss via thermal conduction significantly exceeds radiative heat loss;
- The air-based plasma is in thermodynamic equilibrium;
- The Lorentz force is negligible;
- The radial variation of the electric potential is negligible;
- Viscous dissipation and kinetic energy changes are assumed negligible compared to enthalpy changes due to the ohmic heating.

A critical factor in this study is the total enthalpy required to generate the velocity profiles inside the high-power arc-jet constrictor. Achieving this enthalpy depends heavily on the arc-jet operational conditions, including the input current, voltage, air mass flow rate, and constrictor geometry. This section presents the operating conditions for the working air plasma within the constrictor, where the maximum centerline temperature reaches 10,000 K at a pressure of 1 atm.

Figure 1 illustrates the behavior of specific heat across different temperature ranges. This parameter is utilized in Equation (1) to estimate the enthalpy generated by a 500 A, 400 V electric arc sustained within the constrictor domain.

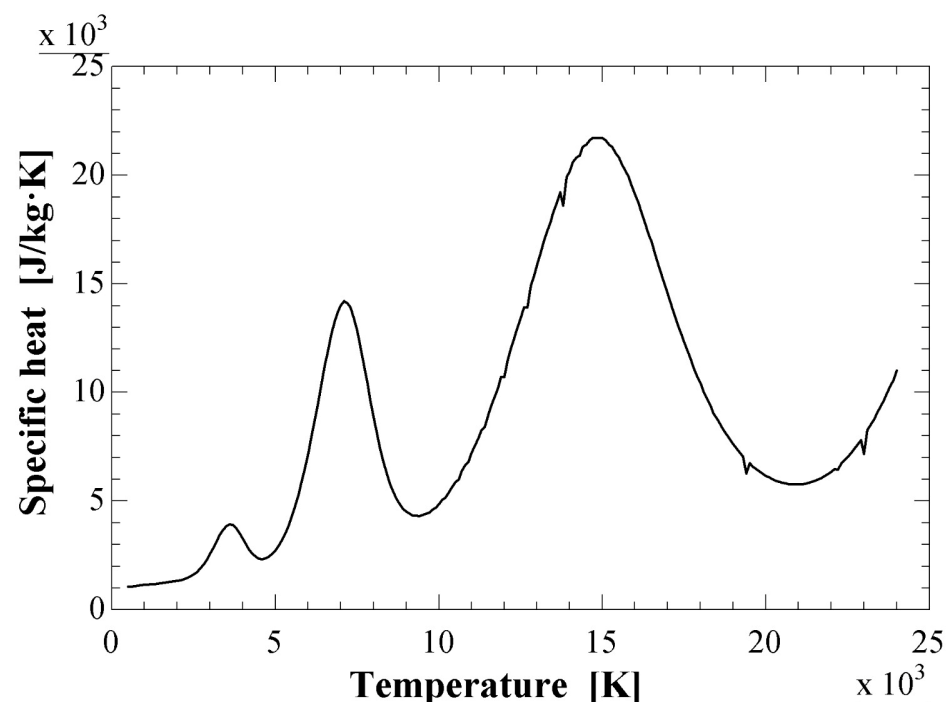


Figure 1. Specific heat at constant pressure vs. temperature (K) at 1 atm, plot created by Marrón [14], based on data provided by Boulos [15].

Wallner et al. [13] established that the typical geometric characteristics of a 200 kW constrictor fall within the following ranges:

$$6.35 \text{ mm} \leq d \leq 25.4 \text{ mm}$$

$$25.4 \text{ mm} \leq Z \leq 152.4 \text{ mm}$$

Based on these reference intervals, the constrictor dimensions selected for the present study are a length (Z) of 101.6 mm and a diameter (d) of 12.7 mm.

Table 1 shows the parameters proposed for this analytical study, where some operational aspects of the arc-jet constrictor have to be considered, beyond the geometric factors, in order to compute the enthalpy magnitudes. The following values are involved:

Table 1. 200 kW arc-jet constrictor operational characteristics.

Parameter	Value
Constrictor length (Z)	101.6 (mm)
Constrictor diameter (d)	12.7 (mm)
Constrictor radius (r)	6.35 (mm)
Amperage (I)	500 (A)
Voltage (V)	400 (V)
Electric arc radius (r_e)	3.175 (mm)
Mass flow rate (m)	0.00893 (kg/s)

According to the Stein & Watson assumption [6], the arc is assumed to fill a large part of the constrictor. As the propellant passes through the arc, the interaction can be represented as follows:

$$\rho u \frac{\partial h}{\partial z} = \sigma E^2 + \frac{\partial^2 S}{\partial r^2} + \frac{1}{r} \frac{\partial S}{\partial r} + \frac{\partial^2 S}{\partial z^2}, \quad (1)$$

where ρ is the density, u is the axial velocity, E is the electric field (assumed constant), σ is the electrical conductivity, and S is the thermal conductivity function; the thermal and electrical conductivity parameter values were obtained according to D'Angola [16].

In this case, the model includes the first term of the equation, which represents the rate of energy absorption by the air via the axial specific enthalpy gradient term; the second term is the energy production by Ohmic heating; and finally, the remaining terms represent the rate of heat loss by conduction.

Physical phenomena inside the arc jet constrictor are considered in this analytical study. The first aspect to review is the axial velocity growth: the propellant enters the constrictor as a uniform fluid, and the no-slip condition forces the fluid velocity at the solid wall to immediately drop to zero. Viscous shear stresses retard the fluid layers closest to the walls, creating a growing hydrodynamic boundary layer. Because the total mass flow rate $\dot{m} = \int (\rho * v * dA)$ must remain constant at every cross-section, the slowing down of fluid near the walls forces the fluid in the central core to accelerate. This continuous transfer of momentum from the walls to the center causes the centerline velocity magnitude to grow along the entrance length; it eventually stabilizes into a fully developed Hagen–Poiseuille parabolic profile once the boundary layers merge at the duct centerline [17].

These aspects are combined and significantly influenced by severe thermodynamic and chemical transitions. When the air plasma is at a temperature of 10,000 K, volumetric dilatation happens as oxygen (O_2) and nitrogen (N_2) undergo intense thermal dissociation and subsequent ionization ($N_2 \rightarrow N + N \rightarrow N + N^+ + e^-$). The multi-species ionization dramatically increases the mole number (N), dropping the local plasma density (ρ) by orders of magnitude according to the ideal gas law. In order to satisfy mass conservation, the

massive drop in density forces an enormous secondary spatial acceleration along the axial direction, far exceeding standard isothermal entrance-length acceleration.

The shape and growth of the axial velocity profile are profoundly distorted by non-equilibrium plasma features, such as decoupled electron temperatures (T_e) and heavy-particle translational temperatures (T_h), where $T_e > T_h$ in the regions close to the constrictor walls [18]. In these cold wall regions, the flow characteristics include high density, particle recombination effects, and high viscosity. Conversely, at the centerline of the constrictor a hot core flow with low density, a high ionization rate and high ambipolar diffusion prevails [19]. There is also a viscous stratification of the flow [20] because the plasma dynamic viscosity (μ) varies with temperature. Close to the constrictor walls, recombination suppresses ionization, raising the density and altering the viscosity gradient.

In the ultra-hot core, high ionization alters the collision cross-sections according to Burton et al. [20]. This strong radial gradient in viscosity warps the standard parabolic profile, often leading to highly stretched or “blunted” profiles. In a non-equilibrium state, light electrons diffuse rapidly toward the walls, dragging positive ions (N^+ , O^+ , NO^+) along via a self-induced localized electric field [18]. This spatial charge separation and species transport alter the local molecular weight across the duct radius.

Because chemical ionization and recombination timescales are finite, the plasma is not in Local Thermodynamic Equilibrium (LTE). The axial growth of the velocity profile becomes strictly bound to the chemical relaxation length; the velocity profile cannot achieve a stable, fully developed shape until the multi-species ionization reactions reach a chemical steady state along the duct axis, according to Miller et al. [19].

In order to verify the ideal gas condition of the atmospheric air propellant, a compressibility analysis was performed using the EES Professional Version V9.994-3D[9/14/15], obtaining an overall factor of 0.9955.

Jahn [21] notes that propellant selection primarily depends on two core criteria: specific impulse and frozen flow losses within the mission’s operational range. While these factors are often constrained by broader system-level requirements—such as storage, feed systems, and propellant degradation—they fundamentally depend on the fluid’s underlying thermodynamic properties. For electric propulsion missions specifically, this necessitates a comprehensive evaluation of operating temperatures and local plasma properties, including specific heat, enthalpy, thermal conductivity, and electrical conductivity.

Based on the dimensions of the constrictor and its operational characteristics, the enthalpy distribution in the constrictor domain is expressed as follows [6]:

$$h(r, z) = 9.43 \times 10^{-3} \left(\frac{C_p}{KA^{\frac{1}{2}}} \right) \left(\frac{I}{r_e} \right) \left(1 - e^{-11.5 \left(\frac{Z}{Z_0} \right)} \right)^{\frac{1}{2}} J_0 \left(2.4 \frac{r}{r_e} \right), \quad (2)$$

where $h(r, z)$ is the enthalpy distribution in the constrictor, C_p is the specific heat at constant pressure, K is the thermal conductivity, I is the arc current, r is the internal constrictor radius, r_e is the electric arc radius [22], Z_0 is the length of the electric arc, Z is the length of the constrictor, J_0 is the Bessel function of the first kind and zero order, and A is the conductivity ratio. Atmospheric air is considered an ideal gas propellant.

Based on the analytical process, a group of sequential equations is used to establish the mathematical bridge between the core plasma enthalpy distribution governed by the Stine & Watson framework—Equation (2)—and the structural development of the local velocity fields. To achieve this, a sequential thermodynamic and hydrodynamic coupling is required.

First, the fundamental property relation $dh = Tds + vdP$, where $v = \frac{1}{\rho}$. Under an assumed local isentropic process where $ds = 0$, the differential enthalpy scales with pressure and local plasma density as $dh = \frac{dP}{\rho}$. Additionally, the specific enthalpy change is related to temperature by $dh = C_p dT$.

Assuming the equilibrium air plasma behaves as an ideal gas governed by $P = \rho RT$, and introducing Mayer's relation $C_p - C_v = R$, the differentiation yields the characteristic speed of sound as a function of the local thermal state. This is expressed as $a^2 = \left(\frac{\partial P}{\partial \rho}\right)_s = \gamma RT$ [17]. Considering the constant gas for a specific propellant (S), the definition of this parameter is introduced as $R_S = \frac{R}{M_S}$ [23]. Inserting this specific gas constant into the speed of sound expression yields the final relation for the sonic field in the constrictor region. Related to the velocity field in the constrictor region, a parameter to be considered is the speed of sound (a) which is defined as follows:

$$a = \sqrt{\gamma \frac{RT}{M}}, \quad (3)$$

where γ denotes the adiabatic constant, R is the gas universal constant, T is the temperature distribution of the propellant considering the fluid calorically perfect and M is the molar mass of the air-based plasma.

When the axial speed of sound is obtained at the region of the arc jet constrictor domain Equation (3), the maximum velocity equation of the propellant is deduced as follows: the expansion of a compressible gas is fundamentally a process of continuous energy transformation, wherein thermal energy (enthalpy and pressure) is converted into kinetic energy (directed motion).

The process originates in a state of absolute rest within a reservoir, known as the stagnation point. At this location, the flow velocity is zero ($u = 0$), meaning the fluid possesses its maximum share of storable thermal energy, quantified by stagnation enthalpy (h_0). Assuming the flow expands adiabatically and frictionlessly along a streamline, the first law of thermodynamics dictates that the total energy must be conserved between any two points. This gives rise to the steady energy equation: $h_1 + \frac{u_1^2}{2} = h_2 + \frac{u_2^2}{2}$.

As the gas leaves the reservoir and accelerates, its local enthalpy (h) drops to sustain the simultaneous increase in flow velocity (u). For an ideal gas, enthalpy directly reflects molecular thermal activity and is linked to static temperature through the specific heat constant at constant pressure $C_p = \left(\frac{\gamma}{\gamma-1}\right) * R$.

Substituting this relation transforms the energy equation into a function of temperature: $\frac{\gamma RT_1}{\gamma-1} + \frac{u_1^2}{2} = \frac{\gamma RT_2}{\gamma-1} + \frac{u_2^2}{2}$. Physically, the static temperature (T) governs how fast pressure perturbations travel through the gaseous medium, defining the local speed of sound ($a = \sqrt{\gamma * R * T}$).

Consequently, as the gas accelerates and undergoes thermal cooling, the local speed of sound decreases accordingly. This allows the energy conservation principle to be rewritten as a purely acoustic-kinematic relationship, anchored by the stagnation state constant (a_0): $\left(\frac{a_1^2}{\gamma-1} + \frac{u_1^2}{2} = \frac{a_0^2}{\gamma-1}\right)$.

As the gas channels through the constrictor geometry, it accelerates rapidly. It eventually reaches a critical threshold where the flow velocity matches the propagation speed of its own pressure waves ($u = a = a^*$). At this sonic or critical state, the total energy is distributed in a fixed proportion determined solely by the molecular structure of the gas, represented by the specific heat ratio (γ). The energy equation at this threshold reduces to: $\frac{\gamma+1}{2*(\gamma-1)} * a^{*2} = \frac{a_0^2}{\gamma-1}$ [17].

This state marks an important physical boundary: beyond this point, the flow becomes supersonic, preventing downstream pressure perturbations from traveling upstream to alter the flow conditions. If the supersonic gas expands further into an absolute vacuum (an infinite expansion), it will continue to accelerate. However, the available internal thermal energy is finite.

A theoretical limit is reached when all available thermal energy is depleted and converted into forward kinetic energy, $\frac{V^2}{2} + \frac{a^2}{\gamma-1} = \frac{a_0^2}{\gamma-1}$. Under this extreme limiting state, (1) molecular translation and vibration cease entirely, causing the static temperature to drop to absolute zero ($T \rightarrow 0$); and (2) without thermal energy, the medium loses its ability to transmit pressure waves, causing the local speed of sound to drop to zero ($a = 0$). Evaluating this thermal freezing condition ($a = 0$) in the general energy equation isolates the maximum attainable flow velocity (V_{max}): $\frac{V_{MAX}^2}{2} = \frac{a_0^2}{\gamma-1}$. Finally, linking this infinite expansion limit to the critical sonic state by substituting the sonic reference constant yields the following equality: $\frac{V_{MAX}^2}{2} = \frac{\gamma+1}{2*(\gamma-1)} * a^*{}^2$. Simplifying the coefficients and isolating the velocity term yields the final expression:

$$V_{max} = a \sqrt{\frac{\gamma+1}{\gamma-1}}, \quad (4)$$

After having obtained the values of the maximum velocity (V_{max}) inside the constrictor domain Equation (4), the radial velocity of the air-based plasma distribution can be estimated as follows: The localized thermodynamic state translates into macroscopic fluid acceleration along the constrictor core, but the steady-state energy equation along a core streamline restricts the maximum attainable velocity parameter (V_{max}) under a theoretical infinite expansion where the static temperature approaches zero ($T \rightarrow 0$), as formulated in Equation (4). Then, this centerline boundary condition is mapped across the entire radial domain by introducing the Navier–Stokes momentum conservation equation for a steady, axisymmetric, fully developed laminar flow inside a cylindrical duct, where the localized viscous shear distribution satisfies the following balance: $\tau_{rx} = \mu \frac{du}{dr} = \frac{r}{2} \left(\frac{\partial p}{\partial x} \right)$. Integrating this governing shear stress relation twice with respect to the radius (r), under the physical boundary conditions of a finite centerline velocity at the axis ($r = 0$) and a strict no-slip condition at the solid constrictor wall ($r = R$) [24] successfully isolates the hydrodynamic integration constants. This mathematical progression yields the characteristic parabolic profile that completely governs the local velocity field, as defined in Equation (5):

$$u(r) = V_{MAX} \left(1 - \frac{r^2}{R^2} \right), \quad (5)$$

The axial and radial velocity fields inside the arc-jet constrictor are evaluated to analyze the velocity magnitudes, field distributions and development of the velocity vector profiles within this geometry. It is important to mention that the function of the constrictor element at this arc jet configuration is to provide the necessary enthalpy due to the interaction of the electric arc and the propellant in order to achieve the velocity magnitudes previous to the acceleration of the air-based plasma at the divergent nozzle; the study of the nozzle domain is not considered in the present work.

3. Results and Discussion

The analytical model of the air-based plasma-specific enthalpy in the constrictor was computed using different input variables: air mass flow rate of 8.93×10^{-3} kg/s, current intensity of 500 A, voltage of 400 V, J_0 of 2.4, and pressure 1 atm., considering that the electric arc reaches a temperature of 10,000 K. The axial enthalpy distribution shown in

Figure 2 at different constrictor radii, caused by the interaction of the air mass flow and the electric arc, produces the distribution from the maximum value of radius (0.00635 m) at the center of the constrictor to the minimum value (0.000001 m) close to the wall. According to this image, the physical behavior of the enthalpy profile (curve trend) along the constrictor successfully represents the axial evolution inherent to the Stine & Watson formulation and curve trend description when subjected to these specific operational parameters inside the arc-jet constrictor [6]. This enthalpy distribution was obtained by Equation (2) mentioned in this document.

A distinguishing aspect of the present study is the analytical reconstruction of the velocity field evolution inside the constrictor domain based on the enthalpy distribution predicted by the Stine & Watson model [6]. The obtained results allow visualization of both axial and radial velocity structures throughout the constrictor length, providing information that is not explicitly reported in the original formulation.

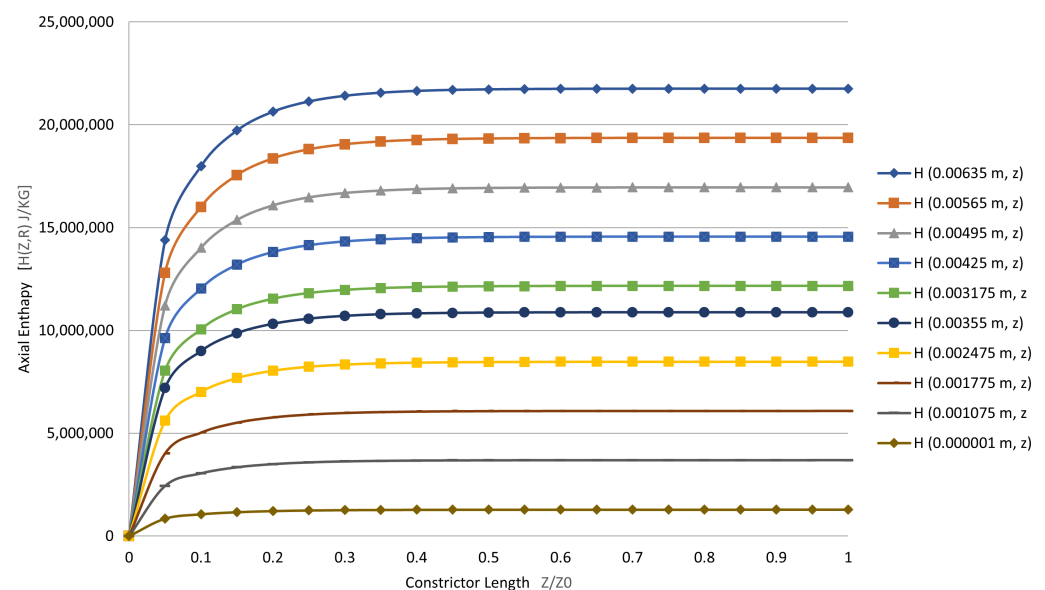


Figure 2. Axial enthalpy distribution at different constrictor radii in 200 kW arc-jet constrictor at 10,000 K.

The presence of the axial enthalpy profiles in the constrictor causes a momentum transfer of the air plasma particles at different radii, producing radial velocity profiles corresponding to a laminar flow inside a duct according to the assumptions established at the beginning of this document. Equation (4) was considered to obtain the local axial velocity magnitudes at different constrictor radii—these can be visualized in Figure 3, where the axial velocity profiles and distribution of air plasma is very similar to those obtained for the axial enthalpy inside the arc jet constrictor. The axial velocity at the center of the constrictor reaches values of approximately 5000 m/s, where the temperature is 10,000 K.

On the other hand, the radial velocity profiles are shown in Figure 4; the momentum transfer of the plasma particles produces different radial velocity profiles corresponding to a laminar flow inside the constrictor. The resulting parabolic shape of the radial profiles mathematically reflects the fundamental laminar flow constraints and thermodynamic assumptions established at the baseline of the analytical model. The presence and development of the radial velocity profile group displayed in Figure 4 are considered at different axial length constrictor stations (Z/Z_0), where the velocity magnitude increases due to the interaction between the electric arc and the atmospheric air propellant along the constrictor. Based on the governing equations of the analytical Stine & Watson model [6], the plasma's enthalpy and velocity fields exhibit a strong coupled dependence on the sys-

tem's operational and geometric variables. According to Equation (2), the local specific enthalpy (h) scales directly with the electrical power input; increasing the arc current (I) at a constant voltage (V) value enhances the ohmic heating term (σE^2)—this term is related to the electric field (E) and electric conductivity (σ). According to Equation (1) this term counteracts radiative energy losses, while the differential expression ($\frac{\partial^2 S}{\partial r^2} + \frac{1}{r} \frac{\partial S}{\partial r} + \frac{\partial^2 S}{\partial z^2}$) governs the conductive heat transfer process. The thermodynamic equilibrium established by the interaction of these mechanisms shifts the local thermal state upward. Consequently, this drives gas expansion and accelerates the maximum axial velocity (V_{max}) which remains physically bounded by the local speed of sound relation ($a = \sqrt{\gamma RT}$). Conversely, the mass flow rate ($\dot{m}$) acts as a convective cooling mechanism ($u \frac{\partial h}{\partial z}$), where higher mass flows distribute the input energy across a larger fluid mass, thereby downscaling both the bulk enthalpy and velocity profiles. Regarding energy concentration, a constricted arc radius (r_e) intensifies the local current density ratio (I/r_e), generating severe centerline enthalpy spikes and higher core velocities, whereas a wider arc yields a more uniform distribution. Finally, the constrictor geometry dictates the flow's spatial development: the total length (Z) governs the asymptotic growth toward a stable velocity plateau through the $(1 - e^{-11.5 Z/Z_0})$ exponential term, while narrowing the constrictor diameter (d) significantly sharpens the parabolic velocity gradient near the wall boundary as described by Equation (5).

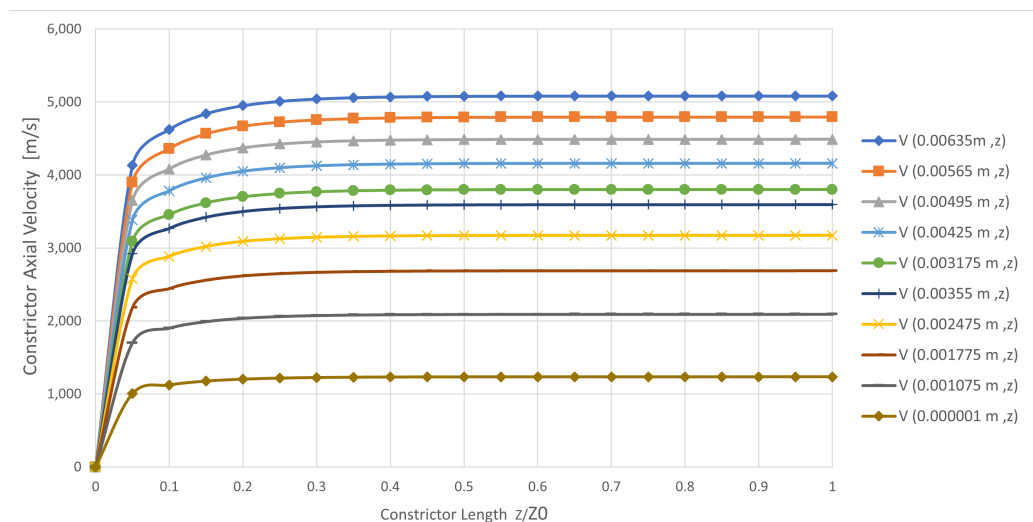


Figure 3. Axial velocity distribution profile at different constrictor radius in 200 kW arc jet constrictor at 10,000 K.

Figure 5 shows the radial velocity profiles at the inlet and the outlet of the constrictor, where velocity reaches 5000 m/s at the outlet. Under these operational conditions, it would be interesting to analyze the subsequent expansion process that the air-based plasma undergoes within a theoretical nozzle domain; unfortunately, the scope of this study is limited to the constrictor domain.

In Figure 6 the air-based plasma radial velocity profiles are shown with their magnitudes included. The figure shows the development of the radial velocity profiles as the plasma flows through the constrictor geometry. The magnitude of each velocity profile increases due to the interaction between the atmospheric air propellant and the electric arc within the constrictor.

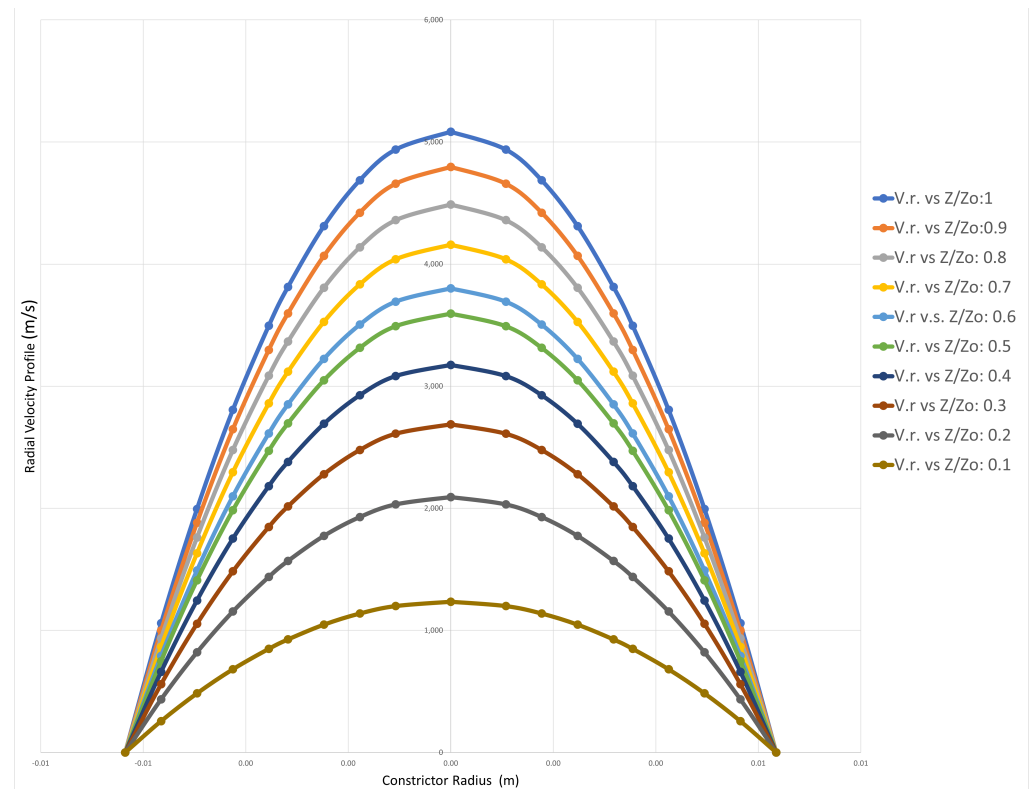


Figure 4. Radial velocity profile at different stations along the constrictor radius in 200 kW arc jet, at 10,000 K.

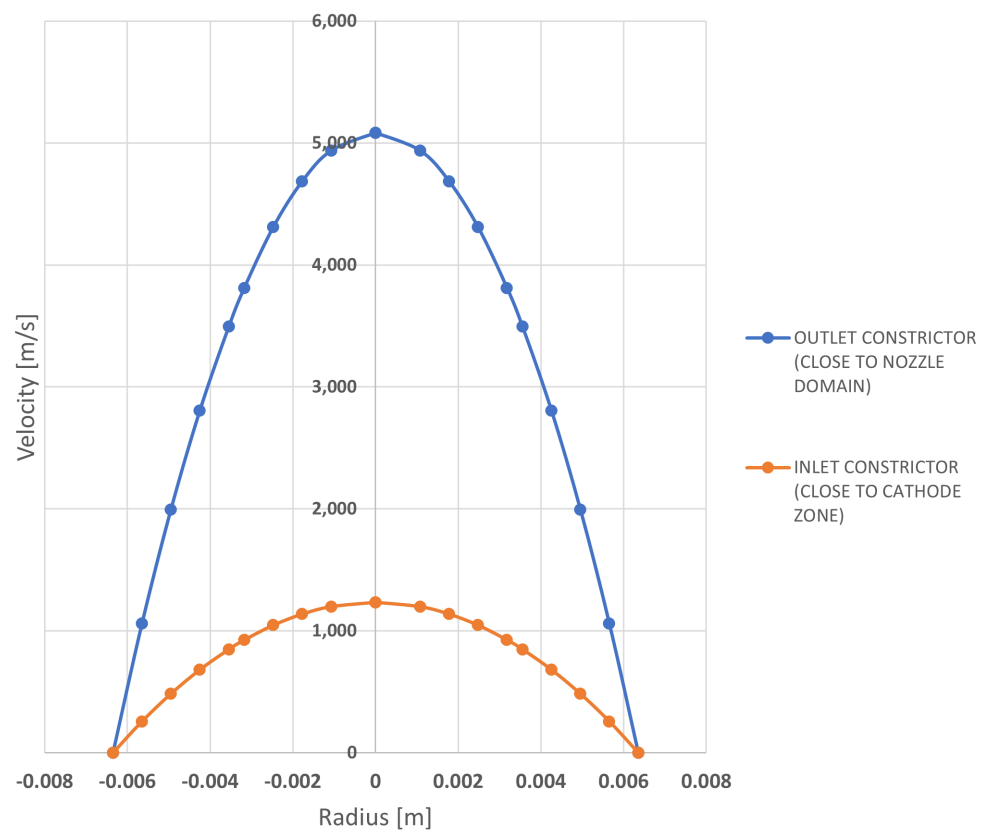


Figure 5. Radial velocity profile at inlet and outlet along the constrictor at 10,000 K.

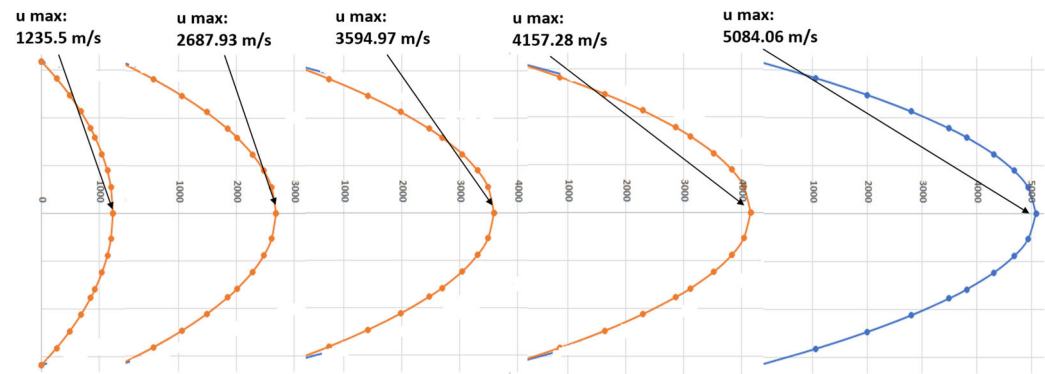


Figure 6. Axial distribution of radial velocity profiles along the 200 kW arc-jet constrictor at 10,000 K.

A direct validation dataset for the 200 kW arc-jet configuration considered in this study is not available in the open literature. Nevertheless, additional support can be obtained from Argumedo et al. [25]. In that work, an analytical formulation derived from the Stine and Watson model was benchmarked against CFD-MHD simulations of an atmospheric-air arc-jet operating under lower power conditions. The comparison yielded discrepancies below 16.328%, indicating that the analytical approach is capable of reproducing the main flow characteristics inside the constrictor. Therefore, while the present comparison should be interpreted as a qualitative consistency assessment rather than a formal validation, previous analytical–numerical agreement provides supporting evidence for the reliability of the methodology employed herein.

The maximum velocity achieved in the 200 kW arc-jet constrictor was 5000 m/s, using atmospheric air as a propellant. This value is significant when compared with the results reported by Argumedo et al. [25], who analyzed the performance of a low-power arc-jet (1–2 kW) constrictor, for which the maximum velocity magnitude value achieved was 3400 m/s, under the same initial restrictions considered for the analytical study at 10,000 K, using atmospheric air as propellant in both cases at a pressure of 1 atm. The comparison highlights the significant difference in amperage magnitudes involved in the process for each case, comparing the behavior of parameters such as electric and thermal conductivity directly affecting the arc-jet variables such as enthalpy and velocity magnitudes stored in the constrictor domain; geometric characteristics have an important effect on the propellant behavior involved in the process, these factors are considered by the Stine & Watson model [6]. The characteristic parabolic distribution of the velocity profiles is consistently maintained in both power scales, as it is a direct consequence of the governing Stine & Watson framework applied.

The velocity profiles obtained in the present study exhibit the characteristic parabolic distribution expected for arc-jet constrictor flows and are consistent with those reported by Argumedo et al. [25], using both analytical and CFD-MHD approaches. Although the operating power considered herein (200 kW) is substantially higher than that analyzed by Argumedo et al. [25], the preservation of the velocity-field structure and the order of magnitude of the predicted velocities, suggest that the analytical framework remains physically consistent across different operating regimes.

Future work will focus on studying the temperature field within the constrictor; it is important to perform studies related to the propellant behavior when the propellant crosses the constrictor outlet and flows into a nozzle domain.

4. Conclusions

The present work extends the classical Stine & Watson [6] analytical approach by employing the predicted enthalpy distribution to characterize the evolution of axial and radial

velocity fields inside a high-power arc jet constrictor. The resulting profiles provide additional understanding of plasma-flow behavior in the constrictor domain, prior to nozzle expansion, and may serve as a useful reference for future analytical and numerical studies involving high-power arc-jet devices.

The obtained results characterize the evolution of atmospheric-air plasma properties within an arc-jet constrictor under the operational conditions mentioned in this manuscript. According to Jahn [21], the flow enthalpy is affected because, in some portions of the flow, the particles experience different slower internal modes such as vibration, dissociation, ionization or recombination that may lag their equilibrium levels and consequently influence the developed velocity fields that will depart from the equilibrium values—this group of events is known as frozen flow. The atmospheric air is not the exception, so the interest of the present analytical study is to visualize the behavior of the enthalpy and velocity fields inside a 200 kW arc jet constrictor. The frozen flow effect combined with other characteristics such as viscosity and thermodynamic conditions (specific heat, pressure, and temperature) results in the curves presented in the Results section. As a reflection and to better understand the analysis, one of the initial assumptions made by Stine & Watson [6] is that viscous dissipation and kinetic energy changes are assumed negligible compared to enthalpy changes due to ohmic heating.

According to the results presented above, it is important to consider air-based propellant as an option to be used on arc jets. Some arc jets of different power ranges use Nitrogen (N_2) as a propellant—this element constitutes 79% of the atmospheric air. According to Jahn [21], nitrogen shows some characteristics such as enthalpy and efficiency of frozen flow (θ_f).

According to some authors such as Duppada et al. [26], the use of atmospheric air as propellant, known as Atmosphere-Breathing Electric Propulsion (ABEP) technology, could help to reduce Very-Low Earth Orbit (VLEO) mission costs; this fact is analyzed and recognized by Andreussi et al. [27]. The effect of ABEP systems on Low Earth Orbit (LEO) mission costs is evaluated and considered by Crisp et al. [28], where electric thrusters are used for this purpose. Although the atmospheric air is a mixture of gases such as Oxygen (O_2), Argon (Ar), Xenon (Xe), the variety of particles contained in this mixture has an effect on the arc jet performance. Future investigations should explore the impact on the thrust generated by the arc jet, using XXI century technologies, in order to satisfy the amount of energy required by this kind of thruster.

A limitation of the present work is the absence of experimental measurements or CFD simulations available for the specific 200 kW operating conditions considered. Consequently, the results presented herein should not be interpreted as a direct validation of the proposed configuration. Nevertheless, previous benchmarking studies based on the same analytical framework have reported good agreement with CFD-MHD simulations, providing indirect support for the methodology adopted in this study. Future work will focus on performing dedicated numerical simulations, and a proposal of some non-dimensional scaling that helps to design an affordable experimental set-up for the configuration.

Author Contributions: Conceptualization, P.J.A.T.; methodology, C.M.R.R.; validation, J.A.M.F.; investigation, L.E.M.R.; data curation, J.A.M.F. and L.E.M.R.; writing—original draft preparation, M.A.V.N. and M.A.C.R.; writing—review and editing, C.M.R.R. and M.A.C.R.; visualization, M.A.V.N.; supervision, P.J.A.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available from the corresponding author upon reasonable request. The data and supporting materials associated with this work are

part of an ongoing research project and are therefore not publicly available. Access is restricted in order to protect sensitive information that could affect future intellectual property registration and related research developments.

Acknowledgments: We would like to express our sincere gratitude to Secretaría de Ciencia, Humanidades, Tecnología e Innovación (SECIHTI) for the Master's scholarship awarded to Joav Alam Morales Flores. We would like to express our sincere gratitude to Universidad Politécnica Metropolitana de Hidalgo for its support in equipment and financing the publication costs.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ABEP	Atmosphere-Breathing Electric Propulsion
AIAA	American Institute of Aeronautics and Astronautics
EES	Engineering Equation Solver
LTE	Local Thermodynamic Equilibrium
NASA	National Aeronautics and Space Administration
VLEO	Very-Low Earth Orbit
LEO	Low Earth Orbit
CFD	Computational Fluid Dynamics
MHD	Magnetohydrodynamics

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