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ENHANCING PLASMA TORCH EFFICIENCY: WET STEAM COOLING

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Abstract. The efficient use of wet steam for plasma torch cooling and water plasma generation is important for reliable plasma generator design. Wet steam, due to phase transformation capability, improves heat removal at lower gas flow rates if compared to liquid water. To evaluate the wet steam cooling potential, a numerical model is proposed, incorporating governing equations (mass, momentum, energy, current, and Ampere's law) are expressed in the cylindrical coordinate system. The model is applied to investigate the wet steam cooling feasibility for the anode of a direct current plasma torch with non-transferred arc. Electric arc modeling examines anode spot location and anode surface temperature distribution for a 120 A arc current and gas flow rates of 42, 90, and 140 l/min under steady flow conditions. Analysis of spatial vapor content distribution in the refrigeration channel highlights unfavorable conditions when wet steam becomes dry.

Keywords: plasma torch, numerical simulation, multiphase flow, heat transfer.

1. Introduction

Growing concerns about global environmental pollution have been fueled by the rapid expansion of industry, which has resulted in industrial, municipal and healthcare waste generation. Addressing this issue requires the development of effective and environmentally friendly technologies to mitigate the negative impact of industrialization on the environment.

Among the various waste treatment methods, thermal techniques have attracted attention for their efficacy in decomposing and/or eliminating hazardous substances [1]. However, these methods face challenges such as the generation of toxic compounds during combustion, which require complex processes for their capture and neutralization.

In this context, thermal plasma waste treatment is emerging as an innovative, energy-efficient and environmentally sustainable alternative [2]. Thermal plasma has the ability to decompose materials at exceptionally high levels, significantly reducing waste volumes and encapsulating harmful contaminants. In addition, its high energy density allows for the use of small equipment and speeds up the heat treatment process [3].

While plasma torches have not been widely adopted due to technological reliability issues, they offer numerous benefits, including rapid gasification of contaminants, waste volume reduction and the production of high value-added products. However, challenges such as high initial cost and complexity of process control need to be addressed [4].

The use of steam plasma has attracted interest due to its unique properties such as high enthalpy and environmental compatibility [5]. Despite existing technical challenges such as electrode erosion and plasma torch lifetime, this technology has the potential to revolutionize industrial waste treatment by providing an efficient and environmentally sustainable solution.

Thermal plasma treatment of municipal solid waste has been shown to be efficient, with the potential to produce cleaner syngas (a mixture of CO and H2) [6]. In [7], synthesis gas with a high content of hydrogen and carbon monoxide, and very low levels of carbon dioxide, light hydrocarbons, and tar was obtained. The measured data, when compared with theoretical computations, confirmed that steam plasma gasification produces syngas with a composition close to that predicted by thermodynamic equilibrium calculations. Thermodynamic analysis helps determine the optimal operating conditions for the plasma reactor to maximize the energy yield of the synthesis gas. Comparative analyses of biomedical waste treatment in air and steam plasma, as well as syngas production through pyrolysis and dry and steam reforming of methane, were carried out in [8] and [9], respectively.

Several water vapor plasma torches have been developed, and key findings regarding the use of water vapor in plasma torches are outlined in references [10–14]. However, these torches typically use auxiliary gases (usually argon), and their thermal efficiency is relatively low because they rely on external water flow for cooling. It would be advantageous to recover the heat dissipated in the electrodes and reintroduce it into the plasma torch. One possible approach is to use wet steam in the cooling channels. As wet steam flows through the cooling channels, it is partially dried and can then be injected into the discharge chamber of the plasma torch, thereby increasing the thermal efficiency of the torch.

In this study, we present the results of an evaluation of the feasibility of using wet steam to cool non-transferred arc plasma torches.

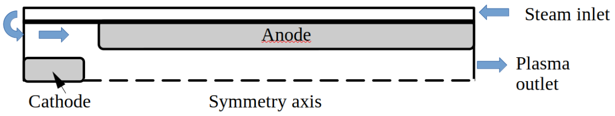

Figure 1. The computation zone

2. Numerical Model

Modeling assumptions: The model is two-dimensional (2D) with axial symmetry; wet steam consists of two continuous components, liquid water and gaseous steam phases; Viscous dissipation, pressure work, and gravitational effects are negligible, and cathode potential drop processes have been omitted. Plasma is a compressible, fully ionized, optically thin, electrically neutral Newtonian fluid mixture at atmospheric pressure in a state of local thermodynamic equilibrium with a low electric field.

The laminar flow model was assumed, which is mainly used to model flows with low and intermediate Reynolds numbers.Mass, momentum and energy conservation equations were applied to the flow simulation, assuming that the flow is compressible.

The complete set of conservation equations representing the equations of continuity, momentum, energy, current continuity and equation of state. The physical property parameters (density, specific heat, viscosity, thermal conductivity, and electrical conductivity, etc) were taken from [15].

Phase change phenomena can occur at a specific temperature (isothermal process) or over a temperature range (process with continuous properties). In the latter case, the thickness of the interface between phases decreases as the phase change temperature range reduces, eventually reaching zero, resembling an isothermal process. This implies the coexistence of both phases on the same interface. The isothermal process is more common in pure substances and eutectic mixtures.

In the energy balance equation, the apparent properties of the fluid were used to account for the transformation of water from the liquid to the vapor state. It was assumed that the phase transformation occurs in a temperature range ΔT, i.e. $\left[T_\mathrm{f}-\frac{\Delta T}{2}, T_\mathrm{f}+\frac{\Delta T}{2}\right]$. In this range, the properties of fluids (liquid and gaseous) are described by a function θ that varies smoothly from 1 (at the beginning of the phase transition) to 0 (at the end) for a liquid state and from 0 to 1 for a gaseous state. Thus, the function θ represents the quality of the vapor.

In this range, the steam quality was utilized to calculate the effective density $\rho = \theta_l \rho_l + \theta_g \rho_g$, thermal conductivity $k = \theta_l k_l + \theta_g k_g$ and specific heat of the fluid:

$$c_p = \frac{1}{\rho}\left(\theta_l \rho_l c_{pl} + \theta_g \rho_g c_{pg}\right) + L_{l\to g}\frac{\partial \alpha_m}{\partial T} \qquad (1)$$

Figure 1 shows the computational domain and its associated boundary conditions. The dimensions are as follows: total length of 90 mm; inner diameter of the anode - 8 mm and outer diameter - 20 mm; anode length is 74 mm; thickness of the cylindrical cooling channel (with steam inlet) is 1 mm. It's important to note that the geometry of the discharge chamber is considerably simplified compared to the actual geometry of the plasma torch used as a prototype.

A constant mass flow condition was imposed at the steam inlet of the plasma torch, while a constant pressure equal to atmospheric pressure was assumed at the torch outlet. Zero flow was assumed on the walls, and zero derivative of the properties was applied on the axis of symmetry. The steam temperature at the entrance to the cooling channel was assumed to be uniform and equal to the saturation temperature for a given pressure at the onset of the phase transition $T_\mathrm{f}-\frac{\Delta T}{2}$, using data from IAPWS (The International Association for the Properties of Water and Steam) [16].

In the arc model, positive ions in the plasma accelerate toward the cathode, generating heat at the electrode surface. As the electrode temperature rises, thermionic emission releases more electrons, resulting in cathode cooling. The electron current density was determined using the Richardson-Dushman equation. For the anode, only electron-induced electrode heating was considered, assuming a work function of $\Phi = 4.15\,\mathrm{V}$.

3. Results and Discussions

The initial focus of the study was to investigate the behavior of the arc in a discharge chamber and to analyze the heat fluxes into the anode wall. Simulations were performed with the arc current limited to 120 A. The gas flow was introduced into the discharge chamber with a slight rotation to improve arc stability. Figure 2 shows the temperature distribution within the discharge chamber of the plasma torch. Calculations were performed in a cylindrical coordinate system, which shows that the arc, bounded by high temperatures, is localized along the axis of symmetry. The plasma temperature exceeds 20,000 K in the vicinity of the cathode, which supports cathode heating and facilitates electron emission necessary for arc sustainment. Electron collection occurs over nearly the entire surface of the anode. The diameter of the arc is bounded by regions of high temperature where free electrons can conduct electricity. Notably, arc contraction, characterized by a reduction in the radial dimension of the high-temperature region, occurs near the cathode, possibly influenced by geometric factors and the presence of a gas vortex. Moving downstream, the diameter of the high temperature region expands due to radial heat transfer and plasma diffusion.

Figure 3 shows the temperature distribution along the plasma torch axis for different gas flow rates. It is evident that an increase in gas flow leads to an

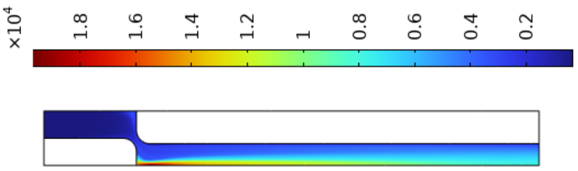

Figure 2. Temperature distribution in the discharge chamber.

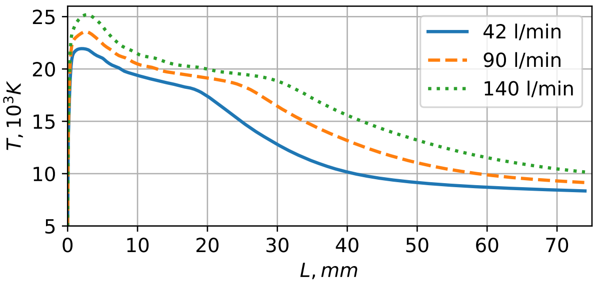

Figure 3. Temperature distribution on the main axis of the torch.

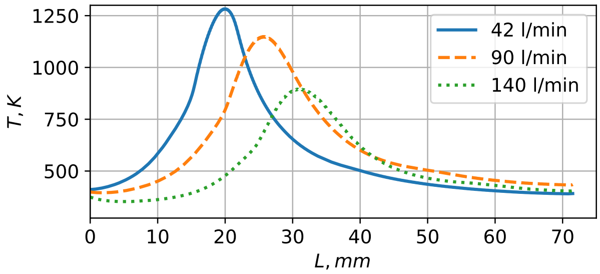

Figure 4. Temperature distribution on the anode surface.

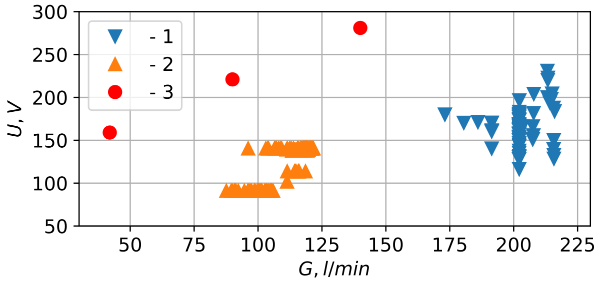

Figure 5. Electric arc voltage versus gas flow. Comparison of experimental and simulated data.

increase in temperature along the symmetry axis, due to the contraction of the arc induced by the growth of the radial pressure gradient. Near the cathode (up to 6–8 mm away), a temperature peak is observed due to the significant arc contraction and the increase in current density.

Following this peak, the gas temperature stabilizes into a "plateau" phase characterized by a slight temperature variation. The extent of this "plateau" phase depends on the gas flow rate and typically ranges from 10 mm to 20 mm for the flow rates modeled. Subsequently, beyond this "plateau", the temperature gradually decreases to the torch exit.

The presence of the axial temperature "plateau" likely correlates with the connection region between the arc axial section and the anode. To validate this assertion, Figure 4 shows the surface temperature of the anode at various gas flow rates, which clearly shows temperature peaks resulting from the passage of the arc current. Comparing figures 3 and 4, it can be seen that the position of the temperature peak on the anode surface corresponds to the extension of the "plateau". It is also apparent that the anode surface temperature is inversely related to the gas flow. As the flow increases, the maximum surface temperature decreases due to the greater volume of gas passing through the discharge and the increased rotational speed. Conversely, the location of the temperature peak is directly related to the flow rate. An increase in flow causes the location of the maximum temperature to shift toward the channel outlet.

Because the numerical model is axisymmetric, it cannot simulate the radial part of the arc, which is a well-localized high-temperature region that rotates about the central axis due to the vortex flow. As a result, the gas flow is perturbed by the motion of the arc on one side and encounters an unobstructed passage of cold gas on the other side. In the assumed model, the radial part of the arc is diffused throughout the entire radial region surrounding the peak temperature on the anode surface. As a result, the gas passing through this region heats up more than in the real case. In fact, the energy balance estimate suggests an average temperature at the plasma torch exit of about 4000–5000 K, while the calculations yield higher values of 6000–7000 K.

The limitations of the axisymmetric model become more apparent when the arc voltage must be determined. The radial part of a real arc forms a column with a very high temperature, which reduces the potential drop required for current passage. In our model, however, the radial part of the arc is simplified as a cylinder occupying the entire radial section of the discharge channel. As a result, the current density decreases with radius, leading to a reduction in heat release and gas temperature. As a result, the region near the anode surface contains colder gas compared to the plasma on the symmetry axis, requiring a greater potential difference for electron passage. Figure 5 shows the arc voltage as a function of gas flow, contrasting simulation results with experimentally obtained data. It can be seen that the arc voltage in the axisymmetric model significantly exceeds the experimental values (about twice as high).

The primary objective of this study is to evaluate the feasibility of using wet steam for anode cooling. By using wet steam, we can utilize the latent heat of phase transformation. To evaluate the effectiveness of the cooling system, we used the temperature

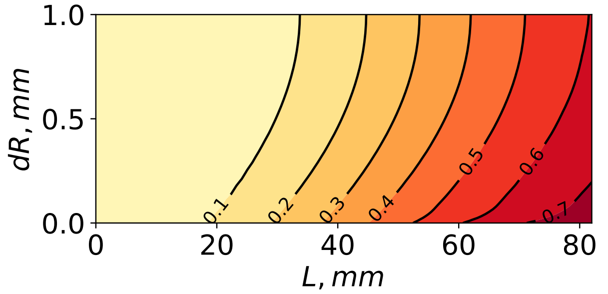

Figure 6. Contour plot of steam quality in refrigeration channel.

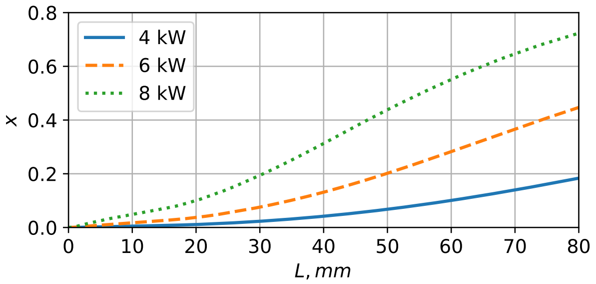

Figure 7. Variation in steam quality along the refrigeration channel for flow rate 6 g/s and heat loads as parameters.

distributions on the anode surface obtained in the simulation, adjusting the heat flux values to match the experimentally measured real values.

Figure 6 shows the distribution of steam quality in the cooling channel for the case of a flow of 6 g/s with a total power dissipated at the anode of 8 kW. Since the thickness of the channel was 1 mm, the figure shows the radial and axial dimensions of the cooling channel at different scales. In this figure, the wet steam inlet with steam quality $\theta = 0$ is on the left side. We can see that in this particular case the steam quality at the outlet of the cooling channel reaches values above 0.7. This demonstrates the viability of using wet steam for anode cooling. Maintaining a relatively low thickness for the cooling channel ensures uniform steam quality throughout each section, maximizing the benefits of phase transformation.

Figure 7 illustrates the effect of heat input (4, 6 and 8 kW) to the anode on steam quality for a gas flow of 6 g/s. The variation in steam quality is calculated along the geometric center of the cooling channel. It can be seen that as the power increases, the steam quality at the outlet of the cooling channel increases in proportion to the total heat flux. At higher heat fluxes, the importance of the temperature distribution at the anode surface becomes apparent, as indicated by the non-linear dependence of steam quality.

4. Conclusions

Plasma-based thermal treatment of waste is an energy-efficient and environmentally sustainable alternative due to its high energy density. However, the widespread use of plasma generators has been hindered by issues such as thermal efficiency and technological reliability. Steam plasma, which offers high enthalpy and environmental compatibility, presents several advantages. To address these challenges, extensive research has focused on developing vapor plasma torches.

This study explores the potential to enhance the thermal efficiency of plasma torches by utilizing wet steam for anode cooling. A numerical model was developed to account for two-phase fluid flow with phase transformation. Simulations were conducted for electric arc discharges of 120 A and gas flows of 42, 90, and 140 l/min. The model that was axisymmetric faced challenges in providing arc voltage data. However, it accurately represented the temperature distribution on the anode surface.

The results indicate that wet steam can effectively cool the torch anode. Specifically, at a flow rate of 6 g/s, wet steam can remove up to 8 kW of heat over an 80 mm anode length and 48 mm inner surface diameter. These findings provide a basis for developing a non-transferred arc plasma generator with fully regenerative cooling, using the insights gained from this model.

Acknowledgements

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