Numerical Simulations of Cascaded Plasma Torch Using Ar and Molecular Gases

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Abstract

In this work, plasma flow inside a cascaded DC torch, effect of a plasma gas composition (Ar or CO_2+CH_4), and torch performance were studied. Both laminar model and k-ε turbulence model were employed and compared in the simulations. The results revealed that carbon contained gases can significantly increase the arc voltage and torch power. This gas mixture increases the arc voltage by up to 200% in comparison with argon. Voltage-current characteristics were also simulated for the current range of 200-400A. Differences in the torch performance can be attributed to the gases specific properties. For instance, at the same temperature the considered plasma gases have similar electric conductivities but the enthalpy of molecular CO_2+CH_4 is much higher. Experimental validation indicates that k-ε turbulence model provides better agreement.

Introduction

Plasma spray has wide-ranging applications in aerospace, automotive, power generation and petrochemical industries to provide protective coatings on components that are exposed to heat, corrosion, and wear. The plasma spraying combines particle acceleration, melting, spreading and solidification in a single operation.

Industrial types of direct current plasma torches usually use argon for plasma generation. Low thermal conductivity and enthalpy of argon, however, limit the thermal efficiency of these torches [1, 2]. Molecular gases such as air, nitrogen are used extensively for plasma generation in waste incineration, steel making, and metal cutting industries. The use of carbon contained gas mixtures has also been reported [3, 4]. The latest, in particular carbon dioxide-hydrocarbons mixture has a number of advantages. Compared with Ar and Ar+H_2, the enthalpy and thermal conductivity of the CO_2+CH_4 mixture is much higher, leading to higher torch power and improved heat transfer to sprayed particles. Additionally, at the arc conditions carbon forms an ionic current toward the cathode, and deposits on the cathode surface, forming an emitting surface of the cathode [4].

In recent development of commercial plasma torch, a cascaded anode is adopted [5]. It consists of several interelectrode inserts insulated from each other. The anodic arc root is forced to remain at the last part of the anode resulting in a longer arc and as a result higher arc voltage. Compared with the conventional single piece anode, the arc with cascaded anode also generates smaller voltage fluctuation.

A new plasma torch has been developed and built at University of Toronto, which has a cascaded anode and a highly structured graphite cathode (Fig. 1). This paper summarizes numerical studies of the effect of different plasma gases and flow mode (laminar or turbulence) on the plasma flow inside the plasma torch. Simulated arc voltages are compared with experimental measurements.

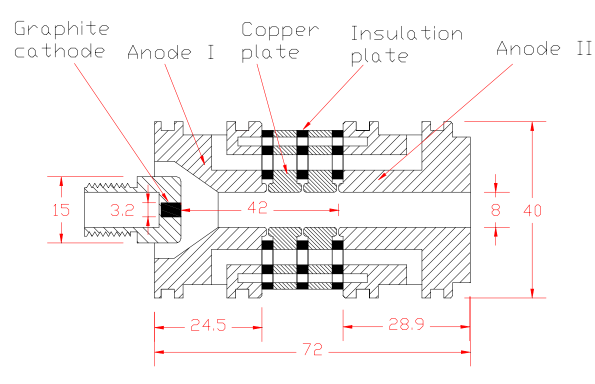


Figure 1: Schematic of the graphite cathode and the cascaded anode (unit: mm).

Working Gas Properties

It is well known that the nature of working gas has a great influence on torch performance and heat transfer to particles. Figure 2 shows the temperature dependence of the thermodynamic and transport properties for two gases, Ar and 22%CH_4+78%CO_2 (in volume). Thermodynamic properties of CH_4+CO_2, such as enthalpy, specific heat and density may be calculated relatively simply once the composition is known, using the mass, enthalpy and number density of each species present. The equilibrium composition calculation is based on the mass action law. The transport properties of CH_4+CO_2 were computed from Boltzmann kinetic theory [6]. The properties for Ar were chosen from [7].

Figure 2a shows that the enthalpy of CH_4+CO_2 is much higher than that of Ar. The reason is that molecular gases must dissociate before ionization. It requires larger energy input thus increasing enthalpy of the plasma. For instance, the enthalpy of CH_4+CO_2 is 290% higher than that of Ar at the temperature of 15000K. In Fig 2.d, it is noticeable that the thermal conductivity of CH_4+CO_2 is much higher than that of Ar in the temperature range of 5000-10000K. For instance, at the temperature of 7000K, the value of thermal conductivity of CH_4+CO_2 is 19 times of that of Ar. Since this is the characteristic temperature of plasma jet, it is evident that CH_4+CO_2 could greatly increase heat transfer to sprayed particles.

Numerical Model

Assumptions

In the simulations, the following assumptions are employed: (i) the arc is in the state of local thermodynamic equilibrium; (ii) the arc is steady, cylindrically symmetrical and optically thin (iii) the viscous dissipation and the pressure work terms in the energy equation are negligible.

Governing Equations

The governing equations are a set of continuity, momentum, energy, and electrical potential equations, which are similar to equations employed in [8], but in a 2D format.

Boundary conditions

The calculation domain and the boundary conditions used in this analysis are specified with reference to Fig. 3. The axisymmetric region ABCDEFHA constitutes the computational domain. This region is divided into 8577 triangle or rectangular cells. At the cathode spot (line DE), the current density distribution is assumed to has the similar form to [9]. When the torch is running, the arc is established between the cathode and the Anode II. Through experiments, we observe the anodic arc root is fixed at the left beginning section of Anode II (indicated by line MN). Therefore the length of the arc can be determined to be 42 mm. On line MN, the electric potential is set to be the anode potential, which is a boundary condition for a fictitious anode. Mass flow rate inlet

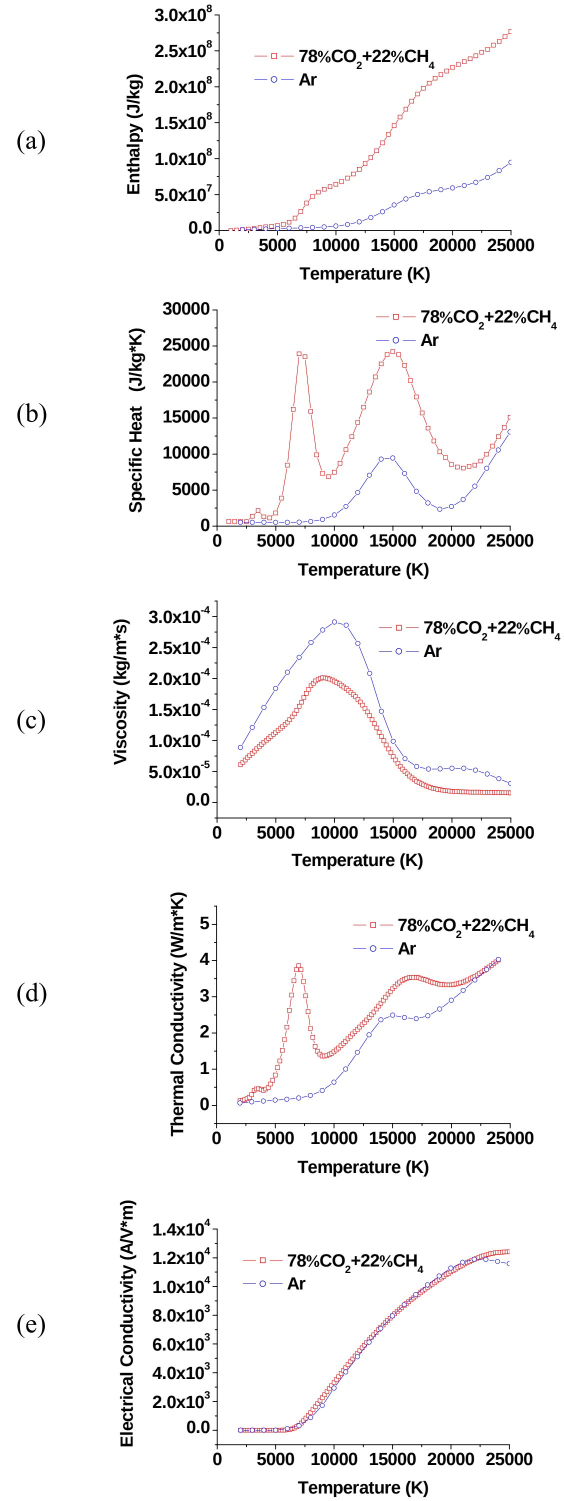


Figure 2: Properties of Ar and CH_4+CO_2 (a) Enthalpy, (b) Specific heat, (c) Viscosity, (d) Thermal conductivity, (e) Electric conductivity.

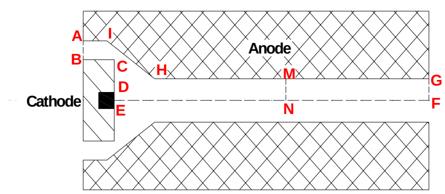


Figure 3: Computational domain for the plasma flow inside the torch.

boundary condition (B.C.) is given on line AB. Wall B.C. are given on AIHMG and BCDE. Axis B.C. is given on EF. Pressure outlet B.C. is given on GF. Based on the data from Westhoff *et al.* [10] the wall temperature on GH is assumed to be 900K.

Results and Discussion

The two-dimensional, axisymmetric, steady-state simulation was performed using the finite volume CFD code FLUENT (Lebanon, NH, USA). An implicit coupled solver with second-order upwind discretization was employed to solve the governing equations. The influence of flow mode (laminar flow or turbulence flow), gas type, arc current (or power) on the temperature and velocity profiles and arc voltage were studied. The two working gases are argon and a mixture of 22%CH_4+78%CO_2 (in volume). The arc current range is 200-450A for Ar, and 200-280A for CH_4+CO_2. The gas flow rate is 32.1 SLPM for both gases.

Arc Voltage

Figure 4 shows the dependence of measured and calculated torch voltages on arc current for Ar and CO_2+CH_4. Two flow modes, laminar flow and turbulence flow, are simulated. For both Argon and the mixture of CO_2+CH_4, laminar mode gives lower torch voltage, and the turbulence flow gives better results compared with experiments. The maximum error of the results from turbulence mode is within 10%, indicating the validity of the turbulent arc model. Therefore, the following results are based on turbulence model.

Comparison of Fig. 4a and 4b shows that use of molecular gases substantially increases torch voltage, hence the torch power. For example, at the current of about 200A, CO_2+CH_4 plasma has a voltage about 200% higher than that of Ar. This difference is due to the molecules that have to dissociate before ionization. This process needs extra energy, causing the increase of torch voltage.

The comparison also indicates different trends of voltage-current characteristic for Ar and CO_2+CH_4. This may be explained by the temperature difference for the arc columns in argon and CO_2+CH_4. The arc column in argon calculated temperature was over 15000 K, and its resistance decreases

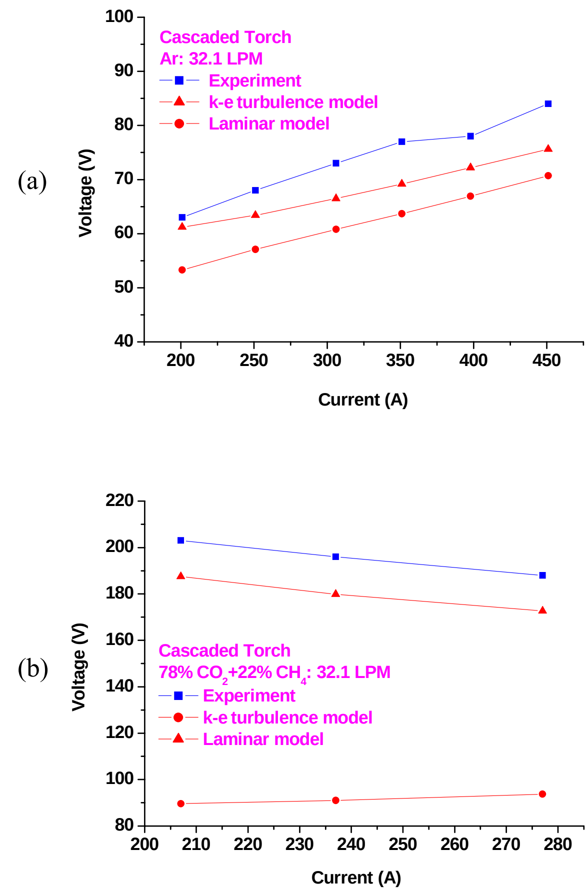


Figure 4: Dependence of measured and calculated torch voltages on arc current (a) Ar (b) CO_2+CH_4.

more slowly than the increase of arc current. Thus, the torch voltage shows an ascending trend. For CO_2+CH_4, the temperature of the arc column was about 12000 K, and the resistance decreases rather quickly than the increase of arc current. Thus, the torch voltage shows a descending trend.

Swirl Velocity Effect and Plasma Radiation Effect

Swirl velocity is often introduced on plasma gas at the gas inlet, which rotates the anode arc attachment and helps protect the anode from locally overheating. Simulations have been performed to study the effect of swirl velocity on plasma flow. The working gas is CO_2+CH_4, arcing at the current of 207A. Swirl velocity is assumed to be 30 times of axial velocity at the gas inlet. Characteristic temperatures and velocities of plasma flow are listed in Table 1. The results indicate that swirl velocity has a maximal effect on maximum temperature of the plasma flow, causing a 6% temperature increase. This happens in the region very close to the cathode, where rotation of the plasma gas is strong and reduces the diameter of arc column, leading to higher current density and increase of plasma temperature. With the increase of distance from gas inlet, the effect of swirl velocity becomes more and more insignificant, and the difference can be neglected at the exit of the nozzle. It can be expected that neglecting swirl velocity will not cause too much error.

Due to the absence of radiation data for CO_2+CH_4, the effect of plasma radiation is investigated on plasma flow. Simulation was conducted with Ar as working gas, arcing at the current of 251A. Characteristic temperatures and velocities of plasma flow are listed on Table 2. It was found that neglecting plasma radiation causes an error less than 4%, which is an acceptable magnitude. Since CO_2+CH_4 plasma generally has a lower temperature than Ar plasma, it can be expected that simulating CO_2+CH_4 plasma flow without considering radiation will not introduce a significant error.

Table 1: Comparisons of characteristic temperatures and velocities of plasma flow with and without swirl velocity component for CO_2+CH_4 at the current of 207A.

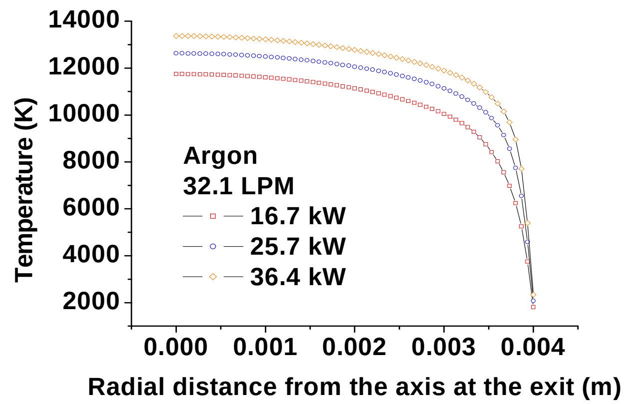
	Voltage (V)	T_{max} inside nozzle (10^4xK)	V_{max} inside nozzle (m/s)	T_{max} at exit (K)	V_{max} at exit (m/s)
With swirl	190.3	1.99	1080	7341	740.5
Without swirl	187.5	1.87	1066	7333	739.7
Difference	1.5%	6%	1.3%	0.1%	0.1%

Table 2: Comparisons of characteristic temperatures and velocities of plasma flow with and without consideration of plasma radiation for Ar at the current of 251A.

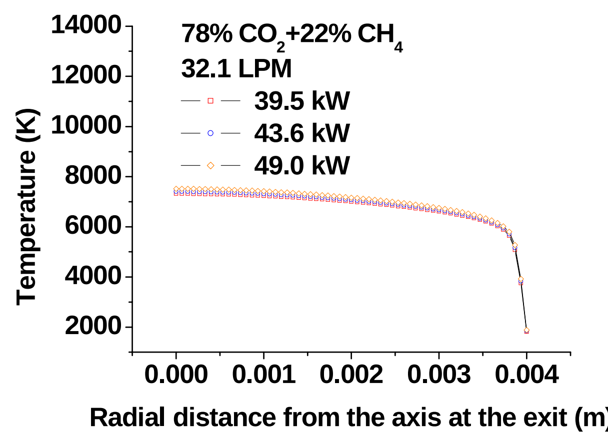
	Voltage (V)	T_{max} inside nozzle (10^4xK)	V_{max} inside nozzle (m/s)	T_{max} at exit (K)	V_{max} at exit (m/s)
With Radiation	64.5	2.07	716	11825	623
Without Radiation	62.3	2.12	735	12000	644
Difference	3.4%	2.4%	2.7%	1.5%	3.4%

Temperature and Velocity Distributions

The calculated temperature contours inside of the nozzle of the cascaded torch working with Ar or CO_2+CH_4 reviled that in both cases, the highest temperature region is very close to cathode. In this region the effect of the cold, stabilizing gas flow from the gas distributor is minimal, then the temperature of the plasma gas drops quickly due to the mixing of the cold gas with hot plasma. For both plasma forming gases the temperatures maintain the highest values along the nozzle axis. Compared with argon, the average temperature of CO_2+CH_4 plasma is about 3000K lower, even though more power is dissipated in the mixture. Figure 5 shows the radial temperature distribution at the exit of the nozzle for several power levels of the cascaded torch. Results demonstrate that the temperate of plasma gas increases with the increase of the torch power. As inside of the nozzle, the gas temperature at the exit has a highest value along the axis, and gradually drops when the distance from the axis is increased. In the wall vicinity, at distance about 3.5mm, the temperature decrease is stronger. The presented data also indicates that argon has a much higher exit temperature than that of CO_2+CH_4.



(a)

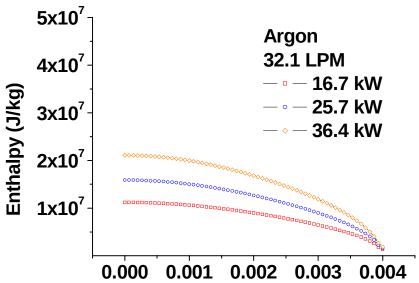


(b)

Figure 5: Calculated temperature distribution at the exit of the nozzle of the cascaded torch (a) Ar, (b) CO_2+CH_4.

Although argon has higher plasma temperatures, calculations found that enthalpy of CO_2+CH_4 mixture is about two times higher than the argon plasma at the nozzle exit. As it was mentioned earlier, this is because the molecular gases mixture requires additional energy for dissociation. Calculated enthalpy profiles presented in Fig. 6.

(a)



(b)

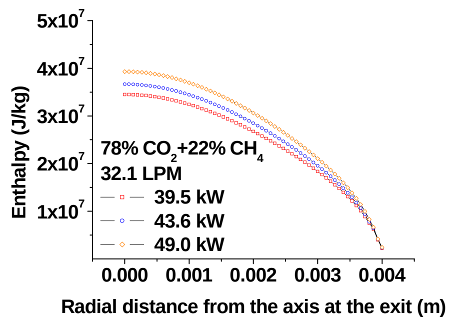
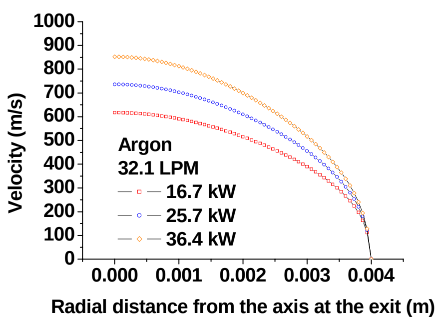


Figure 6: Calculated enthalpy distribution at the exit of the nozzle of the cascaded torch (a) Ar, (b) CO_2+CH_4.

(a)



(b)

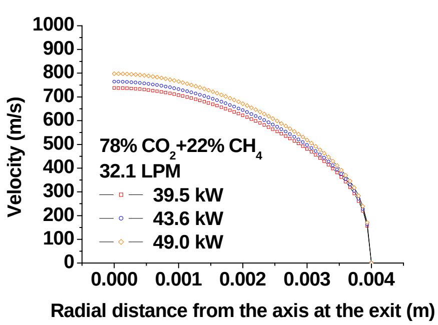


Figure7: Calculated velocity distribution at the exit of the nozzle of the cascaded torch (a) Ar, (b) CO_2+CH_4.

The calculated velocity distributions at the exit of the nozzle of the cascaded torch are given in Fig. 7. It can be seen that increasing torch power helps increase the gas velocity. Though, the effect is less pronounced for the molecular gases. The exit velocity decreases gradually with the distance from the axis.

Conclusions

Simulations in this paper indicate that the turbulence model gives more reasonable results than laminar model. The arc voltage and torch power can be effectively increased by using molecular gases. The swirl velocity component and plasma radiation are found to have minor effect on plasma flow inside the nozzle. Increasing torch power leads to the increases of gas enthalpy, temperature and velocity at the nozzle exit, which are important process parameters for deposition of high quality coating.

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