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Modelling and diagnostics of a supersonic DC plasma jet expanding at low pressure

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The Low Pressure Plasma Spraying (LPPS) technology has emerged as a successful process for the deposition of numerous coatings. However, very few fundamental studies have been conducted in order to better understand the various phenomena controlling the process. This paper presents a combined measurement/model approach that is used to map the characteristics of an argon plasma jet in LPPS conditions. The numerical model is validated against enthalpy probe measurements and good agreement is found. The use of a CCD camera confirms the structure of the jet predicted by the model and also shows that the shock-probe distance that is usually neglected should be considered to avoid significant errors in the mapping of the jet. This combined approach is used to overcome the problem related to the use of enthalpy probes in aerodynamic non-equilibrium plasma jets. The model is used to determine the plasma jet static pressure field, otherwise unknown, which is required by the enthalpy probe technique for the mapping of the jet characteristics.

1 Introduction

The Low Pressure Plasma Spraying (LPPS) technology uses plasma torches operated at low pressure, which offers several advantages regarding powder/coating oxidation, and extended operation parameters. Under these conditions the plasma jets expand to supersonic velocities. This increases the complexity of their modeling and diagnostics, with respect to standard subsonic jets used in atmospheric plasma spraying (APS). Even though the LPPS technology is widely used commercially with great success, it is mainly based on empirical developments. The basis of the physical mechanisms that govern them remains to be better understood. Coupled modeling and experimental work is required to further understand LPPS processes for improved quality of the existing coatings and for the development of new commercial applications.
Several modeling works have been reported on plasma jet flows, either inside or outside the torch nozzle, but only a few of them deal with supersonic plasma jets at reduced pressure [1,2]. Moreover, most of the models are not directly validated against relevant experimental data.
In this paper a numerical model is developed and validated with enthalpy probe measurements and imaging of the supersonic plasma jet. This approach allows overcoming some diagnostic problems involved with aerodynamic non-equilibrium jets. In particular it is underlined that the measurement location is often a few millimetres upstream of the tip of the enthalpy probe due to significant shock-probe distances.

2 Phenomenology

Supersonic jets differ in their behaviour from subsonic jets. The major difference is the fact that the former can exit a nozzle at a pressure that is different from the ambient pressure. This can occur because information on the chamber pressure is carried through the flow by infinitesimal pressure waves that travel at the speed of sound with respect to the fluid. When the fluid at the exit plane of the nozzle reaches the speed of sound or higher speed, the pressure waves carrying the chamber pressure information are unable to reach the flow inside the nozzle. Therefore, the chamber pressure is not felt by the flow and the geometry of the nozzle governs the pressure distribution inside the nozzle along with the torch operating conditions, namely the power [3]. In that case, the jet exit pressure can differ from the chamber pressure.
This phenomenon of non-matched jet/chamber pressure, or what we will refer to as aerodynamic non-equilibrium, leads to complications when using the enthalpy probe measurement technique [4]. Figure 1 shows the structure of a supersonic jet in aerodynamic non-equilibrium situation that is used to explain that problem. In this Figure, the exit pressure of the jet is lower than the chamber pressure. It is an over-expanded jet. Natural mechanisms develop to bring the jet pressure back to the chamber pressure. It is shown that oblique shock waves originating from the edge of the nozzle are formed. This mechanism increases the jet static pressure to the level of the pressure of the chamber by turning the flow (from zone a to b). However, these shock waves are reflected on the jet axis. This leads to a second compression of the flow that brings the fluid to a pressure higher than the chamber pressure (from zone b to c) while turning the flow so it is parallel to the axis. The increase of pressure and temperature after the oblique shock waves can be observed by the increased luminosity of the plasma, if the shock is strong enough.

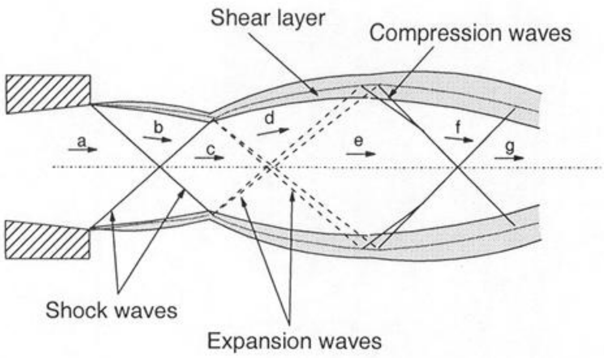

Fig. 1. Compression/expansion mechanisms in an over-expanded jet

The shock waves meet the jet boundary and are reflected in the shear layer in the form of a series of expansion waves. They decrease the flow pressure back to the chamber pressure (from zone c to d). These expansion waves are also reflected on the jet axis so that the flow will then go through another series of expansion waves (from zone d to e) reducing again the flow pressure below the chamber pressure while turning the flow parallel to the jet axis. This is followed by the reflection of the expansion waves into compression waves at the jet boundary, which may coalesce into an oblique shock wave. This is once again forming a second compression/expansion cell, and will be followed by a third, and so forth. The pressure change through each cell is attenuated from cell to cell by the viscous effects, which also thickens the shear layer. Eventually the pressure is brought back to the chamber pressure.

If the Mach number of the flow in zone b is low enough, a simple shock reflection may be impossible to turn the flow from b to c. In that case, a Mach reflection occurs as shown in Figure 2. It consists of an oblique shock and a normal shock, the latter one being located near the jet axis.

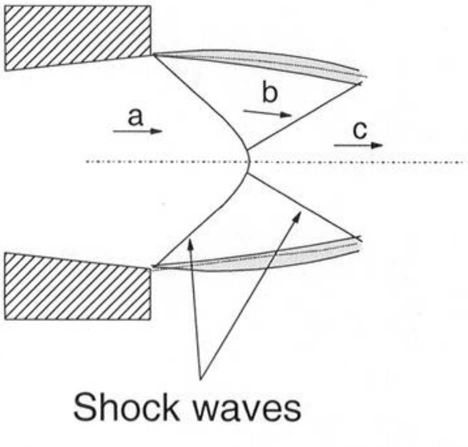

Fig. 2. Mach reflection in aerodynamic non-equilibrium jet

The oscillating pattern of the jet pressure as shown in Figure 1 and the two-dimensional nature of the expansion and compression waves make it difficult to use an enthalpy probe because the free jet static pressure is required to compute the velocity from the probe measurements [4]. The enthalpy measurement technique is therefore confronted to a serious problem when dealing with supersonic jets in aerodynamic non-equilibrium.

The proposed approach to overcome this problem and get an accurate description of the properties of the plasma jet is to use the results of a numerical model combined with the use of an enthalpy probe and a CCD camera. The enthalpy probe is first used to measure the stagnation enthalpy of the flow at various locations in the jet. These measurements are then used to validate a numerical model that will give as a result the two-dimensional oscillating static pressure distribution in the jet that can then be used to compute the velocities that are of interest and complete the mapping of the jet.

3. Experimental set-up and model description

The plasma jet is generated with a Sulzer Metco F4-VB plasma gun with a 6 mm diameter conical nozzle. It is mounted on a 2-axis displacement system inside a $2m^3$ vacuum vessel. For the model validation, the vessel pressure is regulated at 100 mbar by means of a 3-stage pumping system, equipped with a pressure feedback controlled throttle valve. Furthermore, the operating flow rate and electrical current were set at 60 SLPM and 600 A respectively. No secondary gas has been used to avoid the re-strike of the arc and the resulting unsteady perturbation of the flow because this mode is more difficult to characterize and model.

A fast, 12 bits CCD camera (SensiCam from PCO), equipped with a zoom lens and a neutral density filter is used to visualize the total plasma jet emission through a window. The camera exposure time is 100 λs. Figure 3 shows the set-up. It is more thoroughly described in [5].

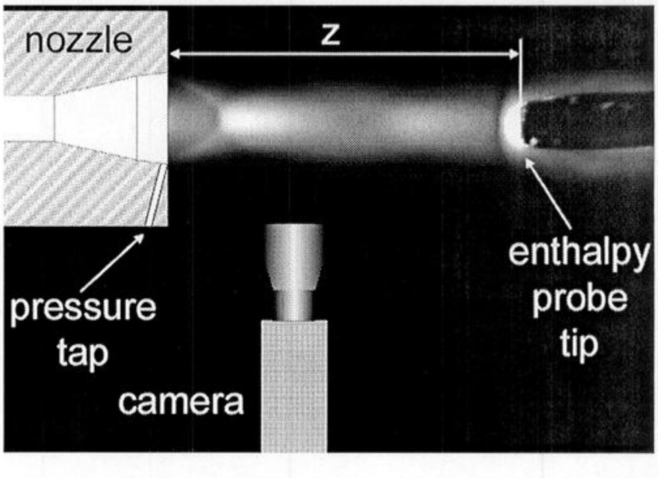

Fig. 3. Experimental set-up

A modified enthalpy probe measurement system [6] is used to measure the stagnation enthalpy of the jet with a 4.3/1.55 mm external/internal diameter probe. Measurements of radial profiles were performed at z=18, 26, 34 and 40 mm. The coordinates z is the distance between the exit plane of the gun and the tip of the probe. The stagnation enthalpy profiles obtained are presented in [5].

The model uses the same approach used in [7] with the exception that the commercial solver Fluent is used to solve the governing equations of the plasma jet. These equations are the mass, momentum and energy conservation equations. Turbulence is accounted for by using the k-e model and the perfect gas law is solved to close the system of equations. The plasma properties, namely the thermal conductivity, the viscosity, the constant pressure specific heat and the molecular weight are computed assuming that the plasma is in local thermodynamic equilibrium (LTE). The optically thin assumption is used in the treatment of the radiation. The problem is assumed to be axisymmetric.

For the boundary conditions, it is assumed that the plasma jet exits in a chamber where the pressure is controlled at 100 mbar. The jet exit pressure was fixed at 96.3 mbar according to the static pressure measurement made at the exit of the torch. The velocity and temperature profile at the torch exit were assumed to have the shape found in [7]. The exact magnitudes of the velocity and of the temperature were fixed by trying to match as closely as possible the stagnation enthalpy profile with the enthalpy probe measurements made at z=18 mm and also by ensuring that the mass flow rate of the model matches the measured mass flow rate.

4. Results

The pressure at the exit plane of the nozzle was measured at 96.3 mbar with a static pressure tap located near the exit of the nozzle (Fig. 3). This leads to a slightly over-expanded plasma jet. Figure 4 shows an image of the plasma jet generated under the specified operating conditions. Figure 4-A (on top) is the picture as taken while Figure 4-B (on bottom) is the same picture but once an Abel inversion has been performed. Note that the bright emission line in the middle of the jet is an artefact due to the sensitivity of the Abel inversion algorithm on axis.

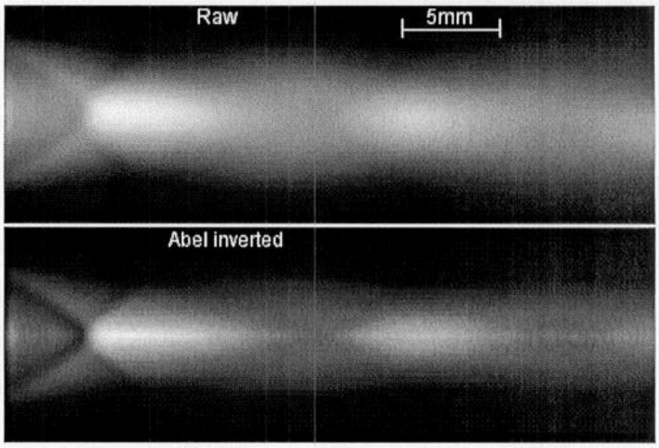

Fig. 4. Image of the plasma jet at 100 mbar chamber pressure, as taken ("raw"), and after an Abel inversion. Torch parameters : 600 A, 60 SLPM Ar

The structure of the jet does exhibit the features of an over-expanded jet. This is shown in Figure 4-A by the initial decrease of the jet width. The oblique shock waves formed at the exit of the nozzle can be seen in Figure 4-A. It is seen from Figure 4-B that they are weak shocks since a very small change in the plasma luminosity is noticed. This was expected since the difference between the jet pressure and the chamber pressure is very small. It is also suspected from Figure 4-A that there is a large Mach reflection. However, the Abel inverted picture indicates that this Mach reflection is in fact very small. The increased luminosity near the axis reveals that the supersonic flow has passed through the Mach reflection and has become subsonic, transferring a substantial amount of kinetic energy into thermal energy. The reflected oblique shock waves are weak and do not slow the jet to subsonic speed. Therefore, after the Mach reflection, the plasma flow is subsonic near the axis and remains supersonic outside that tiny region. As presented in Figure 1, the oblique shock waves are then reflected on the jet boundary and form expansion waves. This increases the plasma velocity while it decreases the temperature. A second compression/expansion cell is present in the flow as it is noticed that a second zone of increased luminosity is present. However, this second cell does not include a Mach reflection but only weak oblique shock waves.

It is concluded that the position z=18 mm corresponds to the zone "e" of Figure 1, where a pressure minimum should be recorded, with a velocity maximum. Accordingly, the location z=26 mm corresponds to the zone "g" in Figure 1 where a maximum pressure should be recorded with a minimum velocity.

The enthalpy probe measurements are used to validate the numerical model. Figure 5 presents the comparison of the stagnation enthalpy profiles between the model and the measurements at z=18 mm (Fig. 5-A) and z=26 mm (Fig. 5-B). It is seen that there is a good agreement in the hot core of the jet. However, the model overestimates the width of the jet after the location z=18mm, causing a larger high total enthalpy zone. More work on the model needs to be done to improve that aspect.

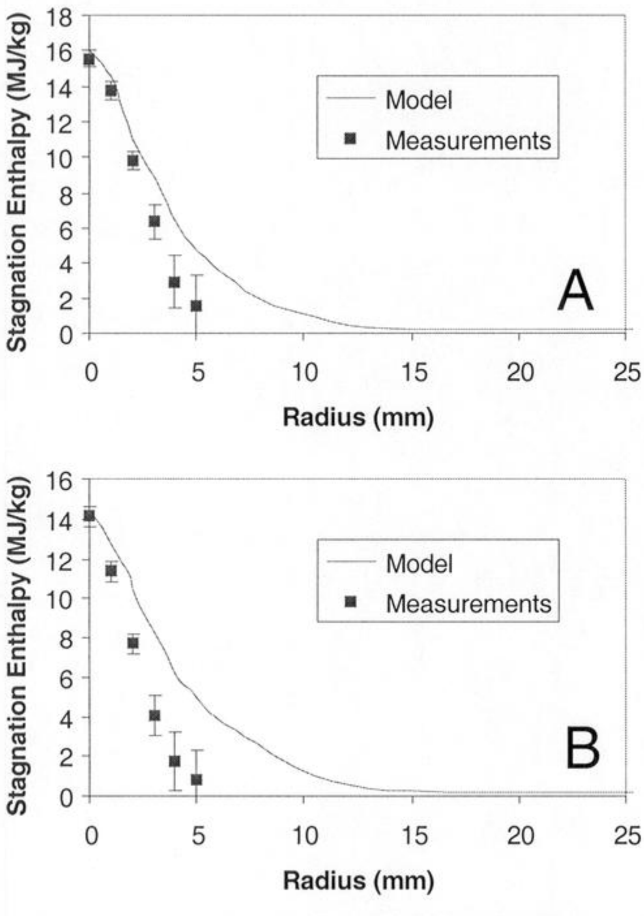

Fig. 5. Comparison of the stagnation enthalpy between the model and the measurements. Case A for z=18 mm. Case B for z=26 mm.

It should be noted that enthalpy measurements suffer from an large error at the edges of the jet because the sampled gas flow is strongly reduced due to a smaller dynamic pressure.

Figure 6 shows the pressure field predicted by the model. This confirms the observations on the flow structure made previously, based on the image of the jet of Fig. 4. The small Mach reflection is located where the pressure contours are perpendicular to the axis.

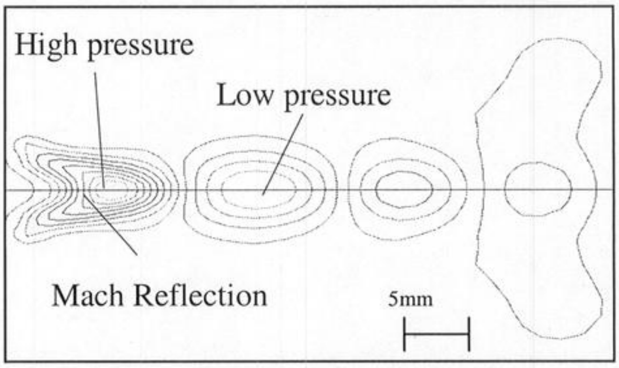

Fig. 6. Pressure field predicted by the model.

Figure 7 shows optimized images of the probe tip on jet axis taken during the measurements for the z=18 mm case and the z=26 mm cases. It is seen that the shock-probe distance is larger in the z=26 mm case.

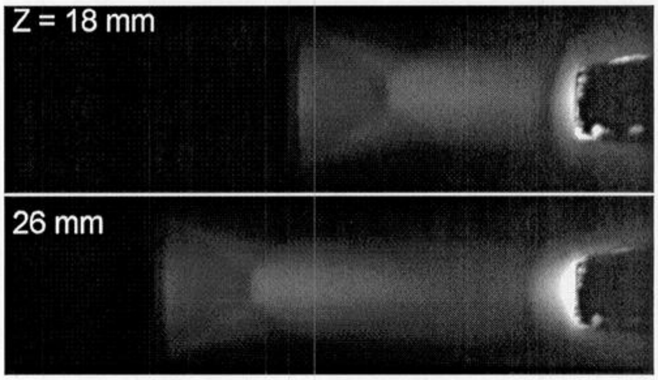

Fig. 7. Images of the probe on the plasma jet axis at z=18 mm and z=26 mm, for a chamber pressure of 100 mbar. Torch parameters: 600 A, 60 SLPM Ar.

This underlines another problem when using the enthalpy probe in supersonic flows. That problem is related to the presence of a shock wave in front of the probe. This situation is depicted in Figure 8.

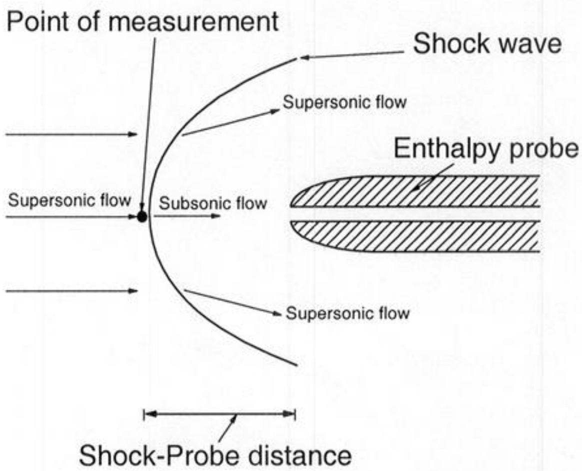

Fig. 8. Supersonic flow around an enthalpy probe.

As the supersonic plasma flow approaches the probe, it has to go through a shock wave to decelerate to subsonic level near the tip of the probe. This shock wave is a bow shock wave, but is usually approximated as a normal shock wave in the region directly in front of the probe. The plasma properties and velocity will experience large changes through the shock wave. The pressure, mass density and temperature will increase while the velocity will decrease to subsonic level. These changes can easily be accounted for when using the probe and assuming isentropic stagnation [4]. However, the use and interpretation of the probe measurements can be misleading. The properties of the flow are measured directly before the shock wave and it is usually assumed [4,8] that the location of the measurement is directly at the tip of the probe. In other words the distance between the shock and the tip of the probe is neglected. This assumption may result in a wrong mapping of the flow properties. Furthermore, if the flow is in aerodynamic non-equilibrium, this enhances the problem denoted previously.

The shock-probe distances observed in Figure 7 confirm the explanation previously given as to what is going on inside the jet. A shorter shock-probe distance means that the flow Mach number is larger since the shock layer thickness decreases with the Mach number [9]. Therefore, as it was already found from the flow structure observation, the shock-probe distance confirms that the Mach number is higher at z=18 than z=26 mm.

Figure 9 presents the shock-probe distance measured for various probe locations on the jet axis. It shows that the shock-probe distance can be large. In this specific case the maximum distance was close to 3 mm. This distance should therefore be used to correct the reported location of the flow measurement. This procedure was used in the validation procedure step of the numerical model.

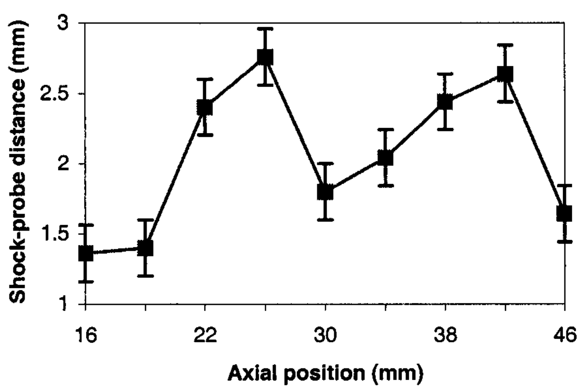

Fig. 9. Shock-probe distance, as determined from the images taken during the measurement with the probe on jet axis.

The validated model is now used to show that errors in the measurement location of a few milimeters can lead to large mistakes in the mapping of the measured properties when the jet is under a strong aerodynamic non-equilibrium condition. Figure 10 illustrates the computed static pressure profile on the axis of an under-expanded plasma jet. The jet exit pressure is 48 mbar while the chamber pressure is kept at 20 mbar. It shows very large oscillations of the pressure over small distances. This case shows that if the shock-probe distance is not considered, a significant error in the pressure used to compute the Mach number, velocity and flow properties may be induced

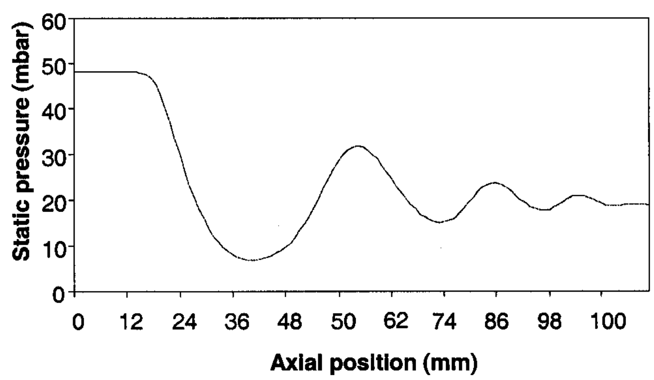

Fig. 10. Simulated axial profile of the jet static pressure, for an under-expanded flow with 48 mbar exit pressure and 20 mbar chamber pressure.

4 Conclusions

A numerical model of an argon jet exiting a LPPS torch has been developed and validated against enthalpy probe measurements for a slightly over-expanded plasma jet at a 100 mbar chamber pressure. A good agreement is generally found between the model and the measurements. The visualisation of the jet light emission using a CCD camera shows the presence of a small Mach reflection in the first compression/expansion cell while only oblique shock waves are present in the second cell. This jet topology is also observed in the model results.

The images of the enthalpy probe on the axis of the plasma jet reveal that the shock layer, or shock-probe distance, varies according to the axial location of the probe. It is shown that these distances depend strongly on the jet local Mach number and that they are as large as 3 mm. Since the measured jet properties are made upstream this shock layer, it is concluded that these distances should be accounted for if a precise mapping of the plasma jet characteristics is sought.

The validated model is used to predict the static pressure variations throughout the flow. This pressure field, which is required by the enthalpy probe measurement technique to map the jet characteristics, is shown to be highly non homogeneous, and can hardly be directly measured in aerodynamic non-equilibrium flows.

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