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Michel Vardelle, Armelle Vardelle, Pierre Fauchais, C. Trassy, P. Proulx. EXPERIMENTAL AND NUMERICAL INVESTIGATION OF POWDER VAPORIZATION UNDER THERMAL PLASMA CONDITIONS. Journal de Physique Colloques, 1990, 51 (C5), pp.C5-171-C5-180. 10.1051/jphyscol:1990521 . jpa-00230828

HAL Id: jpa-00230828

<https://hal.science/jpa-00230828>

Submitted on 1 Jan 1990

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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF POWDER VAPORIZATION UNDER THERMAL PLASMA CONDITIONS

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RESUME

Cet article présente une étude expérimentale, par spectroscopie d'émission, de l'évaporation d'un grain isolé traité dans un jet de plasma d'arc. La température dans le nuage de vapeur qui se développe autour du grain est déterminée à partir du rapport d'intensité de 2 raies mesurées simultanément.

Le rayon du nuage de vapeur est déduit de la mesure de la vitesse des grains au même point de mesure par anémométrie laser et la concentration des atomes métalliques est calculée à partir du profil d'intensité d'une raie en supposant connue la température. Une étude numérique menée en parallèle de l'étude expérimentale permet de prédire le chauffage et l'évaporation d'une particule isolée (sphérique) immergée dans un plasma infini au repos. Les résultats présentés concernent des grains de fer traités dans un jet de plasma argon-hydrogène.

ABSTRACT

For a basic understanding of the interaction of thermal plasmas with powders, a technique based on emission spectroscopy to investigate the vapour cloud surrounding a single particulate has been developed. The temperature within this "diffusion zone" is determined by the intensity ratio of two lines simultaneously measured. Its radius is deduced from the measurement of particulate velocity by laser doppler anemometry and the vapour concentration is calculated from the line intensity profile, once temperature is known. A specific computer algorithm of data acquisition and signal treatment allows systematic measurements. Parallel to the experimental study, a model has been developed to predict the heating and the vaporization of a single particulate (assumed to be spherical) immersed in an infinite stagnant plasma. In a first approximation, thermodynamical equilibrium at the particulate surface is assumed. Results on iron particulates injected in an argon - hydrogen dc plasma jets are presented.

I - INTRODUCTION

Thermal plasma arc systems are being applied to a wide variety of powder processing including plasma spraying, powder densification, extractive metallurgy and industrial waste treatment /1/.

The control and the optimization of the thermal plasma reactors which are, in general, highly heterogeneous systems require an understanding of the interaction of particulate matter with plasma flows.

In such flows with temperatures of the order of 10000 K, the heating rate of the injected particulates is very high. And these particulates can evaporate after a few millimeters of trajectory /2/ depending on particulate and plasma properties.

When vaporization occurs, mass transfer from the particulate surface towards the plasma gas reduces the effective heat transfer: the enthalpy directed to the surface is used to provide the latent heat of vaporization and to heat the vapor within the boundary layer. The vapor diffusion modifies the plasma gas composition and so its transport properties.

Although a fair amount of experimental work has been conducted on particulates trajectory, velocity and surface temperature distributions in dc plasma jets, little fundamental research has been done in the area of studying particulate vaporization.

In this paper a study of the evaporation of iron particulates in argon - hydrogen dc plasma jet is presented for low particulate loading rates.

II - PRINCIPLE OF THE MEASUREMENTS AND EXPERIMENTAL SET UP

The plasma system is a conventional spraying plasma torch with radial injection of powder at the nozzle exit with an injector of 1.6 mm internal diameter.

The working conditions of the torch are the following:

argon: 45 slm
hydrogen: 15 slm
I = 310A ; V = 65V
torch thermal efficiency: 57%
cylindrical nozzle diameter 8 mm, length 28 mm.

The investigated powder is iron. The particulates, whose diameters range from 22 to 44 μm , are injected into the plasma flow 2 mm upstream of the nozzle exit. The powder mass flow rate is lower than 200 g/h. The used techniques to characterize evaporation and/or vaporization are absorption and emission spectroscopy.

The experimental set up for absorption spectroscopy measurement has been described in details elsewhere /3/.

The absorption technique enables to determine the population density of ground state of iron atoms or ions issued from particulate vaporization. This density is deduced from the absorption coefficient of the plasma determined by measuring the ratio of the flux I_0 of a source at the considered wavelength λ to the transmitted flux I_t through the line of sight. In the investigated zone of plasma flow, the line broadening is mainly due to doppler effect. To calculate the population density and the line broadening, the temperature of the gas must be known. Thus the evolution of the plasma temperature along the torch axis is determined from the absolute emission coefficient of argon line ArI 727.2 nm assuming pressure and composition versus temperature are known. In such measurements, the air pumped in the plasma jet has been neglected according to the calculations of Roumilhac et al /4/ showing the error done on the temperature is below 5% for temperatures higher than 7000K. In the range 6000 - 2000 K, these measurements are completed by a few points corresponding to the melting points of refractory materials such as pure alumina and tungsten. Below 2000 K temperatures were measured using chromel - alumel thermocouples /2/. Both the thermocouple and melting point temperature measurements were corrected for conduction along the stem of the probe and for radiation losses. The temperature evolution of the investigated flow is given in figure 1.

Figure 1: Gas temperature evolution along plasma torch axis.

Measurements are performed along the mean trajectory of the particulates /3/. The absorption length is determined from the enlargement at mid-height of the radial distributions I_o/I_t along this trajectory. For example in our experimental conditions, the absorption length is equal to 7 mm at 50 mm from the torch exit and 15 mm at 100 mm.

The lines used in this study are the following /5/:

for FeI 3906.48 Å

for FeII 4287.4 Å

The emission spectroscopy technique allows determination of the metallic vapor concentration around a single particulate in flight.

The experimental set up shown in figure 2 has been adapted to study, at the same time, two lines of excited iron atoms:

Figure 2: Schematic of the experimental set up used for emission spectroscopy and LDA measurements.

Details of this set up and the experimental procedure have been given in reference /3/. Therefore, the principle of measurements is only briefly recalled dwelling on last improvements brought to the technique.

The image of the measuring volume is made on the entrance slit of a JY HR 1000 monochromator with a magnification of two. The light pulses received by the monochromator when a particulate is passing through the observation zone are simultaneously detected by two optical fibers (200 μ m in diameter). The focal field in the plasma flow corresponds approximatively to a cylinder whose diameter is equal to 100 μ m and length to 15 mm. A synchronisation detector set on an axis perpendicular to the line of sight enables to restrict the length of this cylinder to 1 mm. The signals are processed by an oscilloscope which digitalizes the pulses with a sampling rate of 100 MHz. The data transferred to a HP RS 20 computer are processed using a specifically developed algorithm whose main operations are the following:

- regrouping of points for each signal (each one being made up of 5000 points)
- locating of symmetry axis
- smoothing of the averaged signal
- Abel's inversion.

At present, only symmetric signals are processed (the selection is carried out by form recognition) to perform Abel's inversion.

These operations are carried out for the two signals simultaneously recorded and the temperature is determined from the ratio of the emission coefficients of the two lines (this ratio doesn't depend on the iron atom density but only on excitation temperature).

The FeI lines chosen for this study are the following /5/:

$$\lambda_1 = 3705.6\text{\AA}$$

$$\lambda_2 = 3758.2\text{\AA}$$

The why of the choice of these lines has been explained in reference /6/.

The measurement of the particulate velocity by laser doppler anemometry /2/ enables to change the temporal evolution of the temperature into a spatial one, assuming that the velocity of particulate and its vapor cloud are identical: in this case the signals are almost symmetrical. This assumption is verified for distances higher than 45 mm from the powder injection port, whereas at the beginning of particulate trajectory, the plasma velocity is by far much higher than that of the particulates.

The iron atoms concentration in the vapor cloud is calculated from the line intensity profile once temperature evolution and cloud radius are known. To obtain absolute values for the integral intensities of spectral lines, the radiation of the investigated source is compared to that of a tungsten ribbon lamp with quartz window. This comparison is made under strictly identical conditions using the same optical elements, equal apertures...

The population density N_u of the excited level u is related to the line emission coefficient ϵ_{ul} for the transition $u \rightarrow l$ by the well known equation /7/:

$$N_u = \frac{4\pi}{A_{ul}} \frac{J_{ul}}{hc} \epsilon_{ul}$$

where A_{ul} denotes the transition probability upon the emission of radiation of wavelength λ_{ul} .

Assuming a Boltzmann distribution, the population density of fundamental state N is obtained by:

$$N = \frac{N_u \cdot Q}{g_u \exp(-E_u/kT)}$$

where g_u is the statistical weight of the upper level, Q the partition function and E_u the excitation energy of the upper level.

III - EXPERIMENTAL RESULTS

III - 1. Measurement of iron atom and ion concentration within the plasma flow by absorption spectroscopy.

The evolution of the concentration of iron atoms and ions is shown in figure 3. Each dot in this figure corresponds to a spatial and temporal average contrary to results presented in §3.2.

Figure 3: Iron atom and ion concentration along plasma torch axis.

Measurements were performed from 45 mm upstream of the nozzle exit. Below this distance, iron concentration is too high compared to the power level of the used standard source. In the investigated zone, the ion concentration is lower by three orders of magnitude than the atom one. Beyond 55 mm, ion density is not even measurable.

The iron atom concentration regularly decreases from 3.10^{21} m^{-3} at 45 mm to 4.10^{19} m^{-3} at 110 mm.

III - 2. Study of the temperature and iron atom concentration around a single particulate.

The previous experiments have shown that the density of iron ions is low in the measuring zone so for measurements by emission spectroscopy only atomic spectral lines have been considered.

To determine the radius of the vapour cloud surrounding a single particulate, the velocity of the solid particulate has to be measured (see § 2). Results obtained by LDA on iron particulates are given in figure 4a.

Figure 4a : Evolution of particulate velocity along the mean trajectory. Owing to the density of iron material (7860 kg/m^3), the axial particulate velocity is nearly constant from 60 to 120 mm from the injection point.

Figure 4b gives the radial evolution of the velocity of the particulates as well as the corresponding R.M.S. This figure shows the importance to follow the vapor cloud at a precise location in the jet.

Figure 4b: Evolution of particulate velocity along the mean trajectory. (RMS is the particulate velocity root mean square)

The main results of the investigation of the vapor cloud surrounding a particulate by emission spectroscopy are given in figures 5, 6 and 7.

In figure 5 is shown the evolution of the temperature along the vapor cloud radius at different distances from the injection point (each curve corresponds to the average calculated on ten signals). This temperature decreases drastically from 40 to 50 mm, the difference between the temperatures measured at these distances being in the order of 1500 K, 40 mm corresponding to the limit of the plasma core and 50 mm to the plasma plume. On the contrary in the plume of the plasma jet the temperature doesn't vary between 50 and 70 mm.

Figure 5: Evolution of the temperature along the vapor cloud radius.

At least for distances below 70 mm, it seems that the temperature of the vapor increases very fast in the boundary layer close to the particulate (which temperature is below 3000 K) to reach a mean value either almost constant or with a slowly regular increase up to plasma temperature. Figures 6a and b show examples of concentration calculated respectively at 40 and 60 mm from the temperature profiles and the absolute intensity of one of the iron lines. Very high values can be observed: 4.10^{21} m^{-3} at 40 mm and 4.10^{23} at 60 mm. The radius of the vapor cloud increases with the distance, up to about 60 mm, particulates starting to cool down farther downstream.

Figure 6a: Concentration and temperature profiles.

Figure 6b: Concentration and temperature profiles.

Figure 7 shows the concentration distributions in the vapor cloud for particulates at different distances from the nozzle exit. When comparing these values to those obtained by absorption spectroscopy (see fig.3) it is clear that the concentrations around one particulate in flight are higher than the mean values obtained by absorption. It can be explained when

considering the particulate flowrate (about $2.5 \cdot 10^5$ part/sec) which are diluted in a plasma volume of 20 l/s. Assuming an uniform distribution of the particulates the mean distance between two following particulates is about 40 mm. The integration of the obtained concentration at $z=60$ mm over 40 mm distance gives a mean density of iron atoms of 10^{22} m^{-3} closer to the absorption measurements represented in figure 3.

Figure 7: Concentration distribution in the vapor cloud

IV - NUMERICAL STUDY OF THE EVAPORATION OF A SINGLE PARTICULATE

Parallel to the experimental investigation presented in this paper, a numerical simulation of the evaporation of a single particulate has been made.

The intent of this work is to study the influence of the mass transfer on heat transfer coefficient.

In a first step evaporation of a single isolated particulate in an infinite stagnant gas has been studied.

A spherical particulate, initially at temperature T^* and radius R^* is suddenly subjected to surrounding gas at uniform temperature T . The only convective motion considered is that induced by the evaporation process itself, giving rise to a radial convective velocity in the vapor and gas mixture. Additional assumptions include:

- no second order diffusion effects,
- thermodynamic equilibrium at the interface,
- no pressure variation by evaporation process.

In the particulate, the effects of the temperature gradients and the variation of thermodynamic properties with temperature are taken into account. The transport and thermodynamic properties of the mixture of gas and vapor are calculated from properties of pure gases weighted by mass fraction.

The energy conservation equation in the solid or liquid phase and the energy, mass and species conservation equations in the vapor phase are numerically integrated using finite volume method/8/.

Equations in the solid phase are similar to the ones described by Yoshida et al /9/ who have studied the heating of an iron particulate in a R.F. plasma. The temperature profiles for an iron particulate (40 μm in diameter) immersed in an argon plasma at 5000 and 7500 K are shown in Figure 8; in both cases the wall temperature of the particulate is about 3000 K.

The evaporative flux increases from 19.7 to 35.5 $\text{kg/m}^2 \cdot \text{s}$ when the temperature of the gas increases from 5500 to 7500 K.

The normalized vapor mass fraction for the second case ($T=7500$ K) is given in figure 9.

In the present study, conditions of numerical experiments are different from the experimental ones: computations have been made for pure argon gas and the convection effect on particulate vaporization has not been taken into account, that explains the poor agreement for the evolution of iron vapor around the particulate; the iron vapor diffusion is also enhanced by the plasma jet fluctuations. Moreover, the particulate size is not really known for experimental results.

Figure 8: Temperature profiles for 2 different temperatures of plasma gas.

Figure 9: normalized mass fraction of iron vapor.

V - CONCLUSION

An experimental set up has been developed to investigate the vaporization of a single particulate in flight in a dc plasma jet. It enables to determine the evolution of the temperature and the vapor concentration within the vapor cloud surrounding an evaporating particulate.

Experiments carried out on iron particulates whose diameters range from 22 to 44 μm injected in an argon-hydrogen dc plasma jet at the nozzle exit are presented. They show that the temperature within the diffusion zone is almost uniform close to that of plasma flow, and the thickness of the diffusion zone may be higher than ten times the particulates radii.

A numerical study of a particle vaporization has been made from classical theory of droplet vaporization in a spherically-symmetric stagnant gas at uniform temperature. A better agreement with experimental results, especially for vapor concentration evolution in the diffusion zone, would be obtained by taking into account convection effect on particle vaporization.

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ACKNOWLEDGEMENT

This work has been supported by CNRS-PIRSEM (ARC "Réacteur plasma en phase hétérogène").