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ENERGY AND MOMENTUM TRANSFER TO SPRAY PARTICLES IN ATMOSPHERIC Ar-H_2 PLASMA JET

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ABSTRACT Spatially resolved measurements of the electron density- and temperature in an atmospheric argon hydrogen plasma jet used for plasma spraying have been carried out.

The electron density is determined from H_β broadening. The electron temperature is obtained both from line to continuum ratios and from the electron density assuming LTE population.

Also particle velocities in the axial direction of the plasma jet have been measured with a Laser Doppler Anemometer (LDA).

INTRODUCTION The industrial significance of the plasma spraying process lies in the possibility of the deposition of melted and accelerated micron sized particles upon a substrate, in order to produce a strong mechanical and anti corrosive layer.

The first purpose of our study is to measure plasma parameters like electron density, electron temperature and gas velocity of a spraying plasma. The second purpose is to study energy and momentum transfer from the plasma to the spray particles.

The heat transfer to metal particles is calculated theoretically by using a quasi-stationary model. A one dimensional verification of the quasi-stationary approach is made by means of calorimetric heat content measurements according to Houben et al. [1].

EXPERIMENT The Laser Doppler Anemometer (LDA) shown in fig.1 consists of an argon ion laser, a beamsplitter and a monochromator. The latter serves as an optical filter to separate the plasma light from the scattering signal, which contains the Doppler information. A transient recorder (20 MHz) enables "single particle detection".

The detected frequency is related to the axial velocity component $v_{//}$ through

$$\nu_D = \frac{2.v_{//} \sin \frac{1}{2} \phi}{\lambda_o} \qquad (1)$$

where ϕ is the angle between the two laser beams and λ_o is the laser wavelength (5145 Å). The scattered light of the particles is detected under an angle of 20^o with the horizontal plane F. The detection system consists of two mirrors, M2 and M3, two lenses, a monochromator and a photomultiplier.

Every single Doppler-burst is digitized by the transient recorder and stored in the memory of the micro-processor; 50 Doppler-bursts are added to a noise free curve as shown in fig.2. The frequency νd and the desired velocity $v_{//}$ are deduced from this information by a Fast Fourier Transform (with the Burroughs 7700 computer). The optical system is also used for the measurement of the Stark broadening of the H_β-line and of the ratio of the 4806 argon ion line emission and the adjacent continuum emission. The calorimetric heat content of Mo and Cu particles is determined according to the method developped by Houben et al. [1].

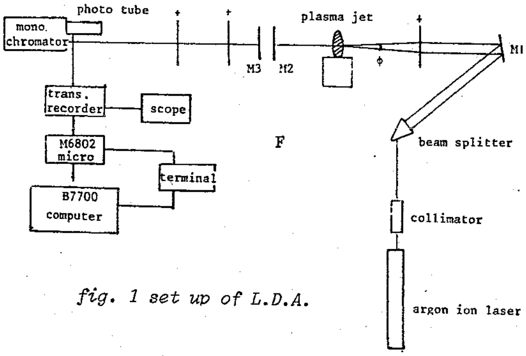


fig. 1 set up of L.D.A.

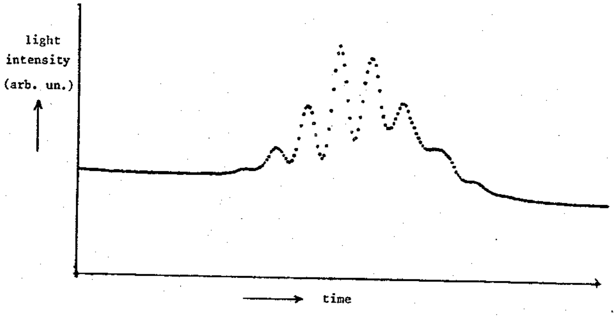


fig. 2 Digitized Doppler burst

THEORETICAL MODEL Calculations and momentum and heat transfer from very hot media like a jet plasma to relatively cold spherical particles is complicated because a plasma is a compressible medium with strong temperature gradients in the boundary layer. This implies spatial dependence of transport coefficients like viscosity η and thermal conductivity λ.

As the number of Prandtl, $Pr = \frac{\eta\ c_p}{\lambda}$ is approximately 1, one can state that the momentum equation is similar to the energy equation. The Reynolds-number is low, so the transport is mainly viscous and not turbulent and the heat transfer is mainly governed by conduction.

We will first treat the heat transfer in a quasi-stationary concept and then evaluate an expression for the particle heat transfer after the passage through the plasma.

The assumptions are :

1. $\lambda_{\text{plasma}} << \lambda_{\text{particle}}$, so we have uniform particle temperature and gradients in the plasma; λ = heat conductivity.

2. Fouriers number $Fo = \frac{a \cdot \tau}{R^2} >> 1$, with a = thermal diffusivity, τ = particle heating time, R = particle heating time, R = particle radius, so a quasi-stationary approach is allowed. This approach is certainly justified for particles with a good diffusivity. The warming up of the particle is now deduced from the heat flux q_n, which follow from the calculated temperature boundary layer, with the particle surface temperature and the plasma temperature as boundary conditions.
For a stationary plasma boundary layer we can write :

$$\nabla \cdot q = 0 \quad q = -\lambda \nabla T \quad \text{so} \quad \nabla \cdot (\lambda(T) \nabla T) = 0.$$

In spherical coordinates we get :

$$\frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \lambda(T) \frac{\partial T}{\partial r}) = 0 \tag{2}$$

with boundary conditions $T(R) = T_p$, $T(\infty) = T_{plas}$.
After performing a Kirchhoff transformation we obtain :

$$\frac{\partial}{\partial r} (r^2 \frac{\partial}{\partial r} [\int_{T(r)}^{T_{plas}} \lambda(T) dT]) = 0 \tag{3}$$

substituting the boundary conditions the resulting heat flux to the particle $\underline{q_n}$ appears to be :

$$\underline{q_n} = - \frac{1}{R} \int_{T_p}^{T_{plas}} \lambda(T) dT \ [\frac{W}{m^2}]. \tag{4}$$

One can prove that (4) is almost independent of the value of T_p, since $T_{plas} > T_p$. For a particle travelling through the plasma via a trajectory s (see fig.3), leaving it at axial position s_o the accumulated conductive heat transfer is :

$$W_p = 4\pi R \int_0^{s_o} \frac{ds}{v_p} \int_{T_p}^{T_{plas}(s)} (\lambda(T) dT) \tag{5}$$

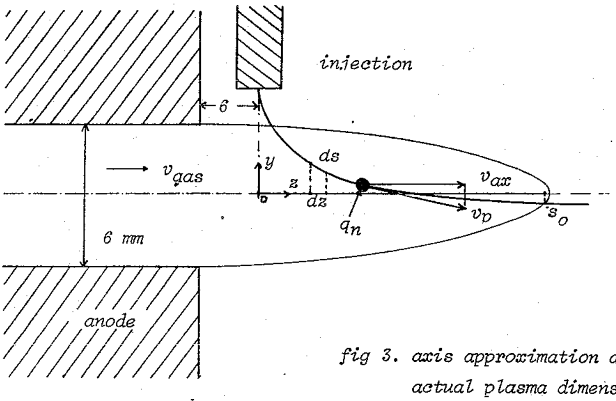


fig 3. axis approximation and actual plasma dimensions

As we measured only the axial component of the particle velocity v_p we calculate the average particle heat content by replacing the actual

trajectory s by a straight trajectory on the plasma axis between 0 and z_o. In this approximation, the particle remains on the axis, where the plasma temperature is maximum which favours the heat transfer.
However in the approximation the dwell time is shorter than the actual one, which reduces the heat transfer.
So, shorter dwell time in the axis approximation is compensated more or less by higher plasma temperature.
A numerical simulation of an extreme traverse axis trajectory, with a relatively long dwell time shows that the heating of the particle is overestimated by 25% in the axis approximation.
The one dimensional form of (5) is :

$$W_p = 4\pi R \int_0^{z_o} \frac{dz}{v_{ax}(z)} \cdot \int_{T_p}^{T_{plas}(z)} \lambda(T)\,dT \qquad (6)$$

Actually, for central axial injection this approximation would be the correct description.

EXPERIMENTAL RESULTS We carried out Laser Doppler measurements in the plasma jet (fig.3) on 40μ Mo and 70μ Cu particles both with and without a few percent hydrogen.

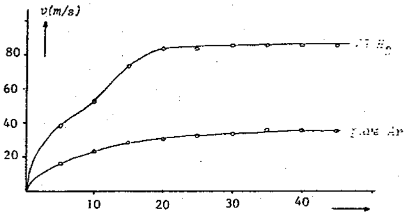


fig. 4 axial velocity of 70 μ Cu

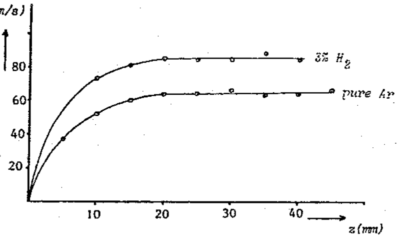
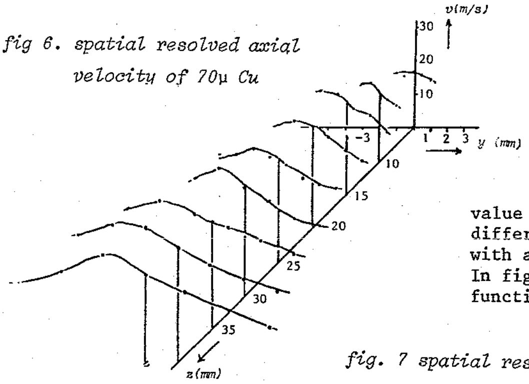


fig. 5 axial velocity of 40 Mo

In fig.4 the axial velocity of 70μ Cu-particles is shown as a function of axial position. It appears that already with a few percent hydrogen the particle velocity is significantly higher than in the case of pure argon. This can be explained by assuming a higher plasma temperature in the former case (confirmed by line continuum measurements of the 4300 Ar^I-line), which results in a higher gas velocity, on basis of the mass-continuity equation. The same situation holds for 40μ Mo-particles (see fig.5), in which case an additional levelling-off of the velocity is measured.
In fig.6 a complete lateral-axial (y-z) scan of the axial velocity component is represented for 70μ Cu-particles in pure argon.
It is clearly to be seen that the maximum of the axial velocity is not on the axis of the plasma but somewhere below. This phenomenon can be explained by the lateral way of injection which is orientated downwards. Thus particles which appear under the axis have passed the area where viscosity ($\sim T_e$) and velocity are maximum. Accordingly their velocity will be higher.
Further we report on the results (see fig.7) of electron density measurements by Stark broadening of the H_β -line, (2) at present without performing Abel-inversion.
From these electron densities the electron temperature T_e can be derived by assuming excitation LTE. Simultaneously with the H_β measurements the Ar^{II}-4806 to continuum ratio was determined which delivered us another

fig 6. spatial resolved axial velocity of 70µ Cu



value of T_e. This value differed from the LTE value with a maximum of 3%. In fig.8 T_e is shown as function of z and r.

fig. 7 spatial resolved electrondensity

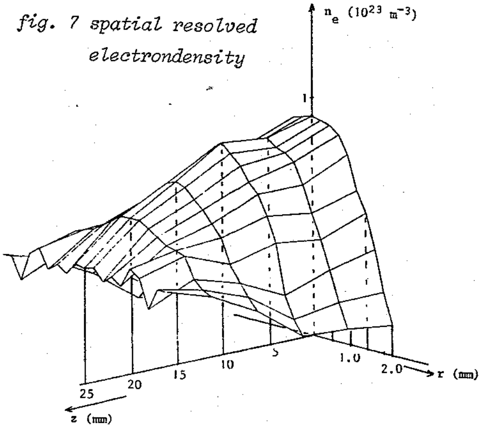
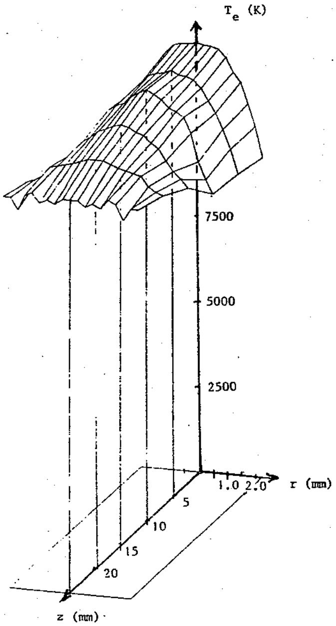


fig. 8 spatial resolved electrontemperature



It appears that the electron temperature decreases 9% along the plasma axis, where we have to consider the axis approximation. The measured axial dependence of the temperature is now used to evaluate the heat transfer to the particle. Since T varies only weakly we take the λ-integral in (5) as a constant function of z taking an average temperature of 12000 K.

$$\text{So:} \int_{T_p}^{12000} \lambda(T)\,dT = 5333\ \frac{W}{m} = C_{12000} \qquad (7)$$

With help of the known Laser-Doppler profiles according to fig.5 and 6 the reduced integral (6)

$$W_p = 4\pi R\, C_{12000} \cdot \int_0^{z_o} \frac{dz}{v_{ax}(z)} = 4\pi R\, C_{12000}\ t_{dwell} \qquad (8)$$

can now be evaluated graphically.
For 40µ Mo, the plasma dwell time appeared to be $3.35\ 10^{-4}$ s, for 70µ Cu it was $4.622\ 10^{-4}$ s. Substituting these values in eq.(8) we finally get for one particle

$W_p^{\ Cu} = 1.08\ 10^{-3}$ J , $W_p^{\ Mo} = 0.45\ 10^{-3}$ J.

Expressing these values per unit of mass, in order to compare it with the calorimetric measurements we get

	W_p model	W_p calorimetric
70µ Cu	675 $\frac{kJ}{kg}$	727 $\frac{kJ}{kg}$
40µ Mo	1340 "	1170 "

The correspondence for Cu between calorimetry and model is 8%, for Mo about 13%.
Even after substracting the 25% for the 1 dimensional overestimation, the correspondence between theory and experiment is still within 30%.

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