ENERGY AND MOMENTUM TRANSFER TO MICRON SIZED PARTICLES IN AN ATMOSPHERIC ARGON PLASMA JET FOR PLASMA SPRAYING.

E.H.Vaessen, J.Arts, J.M.Houben
Interdepartment group on plasma spraying, Eindhoven University of Technology, Eindhoven, The Netherlands.

ABSTRACT

A study of plasma parameters and particle velocities of micron sized particles in an atmospheric argon-hydrogen plasma jet used, for plasma spraying has been carried out. Preliminary determinations of electron density and temperature have been obtained from spectroscopic data. Particle velocities are measured using the Laser Doppler technique. Theoretical values of heat and momentum transfer of a high temperature plasma to spherical particles have been calculated.

1. INTRODUCTION

The industrial significance of the plasma spraying process lies in the possibility of depositing melted and accelerated micron sized particles upon a substrate, in order to produce a strong mechanical layer.
The first purpose of our study is to measure plasma parameters like electron density, electron temperature, ion temperature and gasvelocity 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 the particles is studied theoretically by using a quasi-stationary model.
The momentum transfer to the spray particles can be studied either experimentally and theoretically. In order to determine the final particle temperature, which is a very important parameter in obtaining a strong mechanical layer we will use measured velocities in combination with the measured gastemperature.

2. EXPERIMENTAL

The experimental set up is shown in fig. 1.

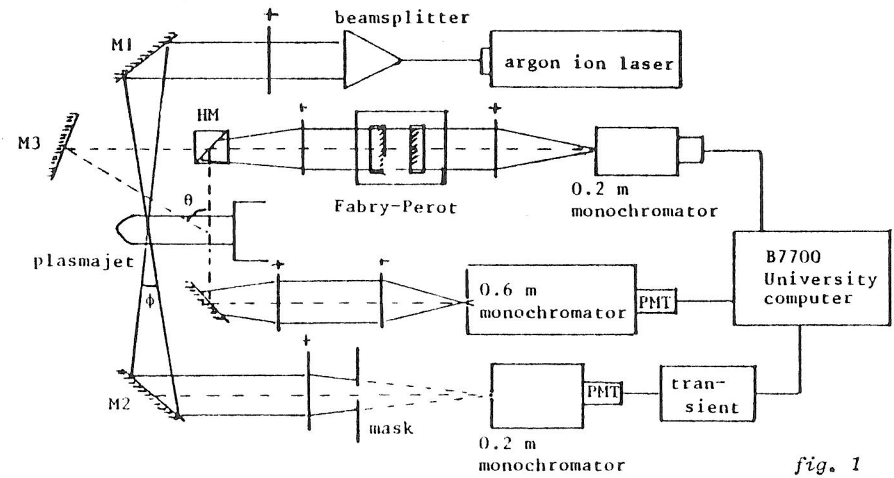


fig. 1

- The Laser Doppler Anemometer consists of an argon ion laser, a beamsplitter and a monochromator which 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" in the case the particle concentration is low.
The detected frequency is related to the axial velocity component v1 through:

$$\nu_d = \frac{v1.2 \sin \frac{1}{2}\phi}{\lambda_o}$$

, where ϕ is the angle between the two laserbeams and λ_o the Laserwave length (5145 Å)

- The second diagnostic of the experiment is a pressure scanned Fabry-Perot interferometer which has a twofold purpose:

1. The ion heavy particle temperature T_i is determined from the width of an argon ion spectral line with relatively small Stark broadening.
   The line profile is fitted with a Voigt profile to separate the gaussion Doppler broadening from the Stark broadening.
   Besides T_i we also want to measure the electron temperature T_e because the transport coefficients like thermal conductivity λ, viscosity η depend strongly on the ratio between T_e and T_i. If for example T_i would be 7500 K while T_e is 15.000 K, Cannapan and Bose [1] calculate that the thermal conductivity increases an order of magnitude compared to the case of equal temperatures $T_i = T_e$ = 15.000 K (LTE). Under the same conditions the viscosity decreases 30%.
2. By looking at a point in the plasma under two different angles one can determine the plasma velocity v_g by measuring the Doppler shift of an ion spectral line.
   As the spectral line is also Stark-shifted, it is useful to use an unshifted standard, which is mixed with the plasma light during the experiment. For this purpose we use the λ= 4580 Å argon-ion laser line at minimum laser power.
   The gas velocity results from the measured Doppler shift $\Delta\lambda$ by:

$$v_g = \frac{\Delta\lambda}{\lambda_o} \cdot \frac{c}{\sin\theta} .$$

- The third diagnostic is a 0.6 m scanning monochromator with a resolution of 120 m Å .
With this monochromator we measure line profiles of the H_α and H_β-lines. The profiles are first abel inverted, and then the electrondensity is determined from the half value width. According to H. Griem[2], values are true within 5%. The electron temperature is obtained by measuring the argon ion line to continuum ratio.
In this case one has to know β_1, the overpopulation factor of the ion-groundlevel, which - in case of PLTE - for our densities will vary between 5 and 10.

3. THEORETICAL MODEL

Calculations on momentum and heat transfer from very hot media like a jet plasma to relativily cold spherical particles is complicated because a plasma is a compressible medium with strong temperature gradients within the boundary layer. This implies spatial dependance of transport coefficients like viscosity and thermal conductivity.

As the numner of Prandtl, $Pr = \frac{\eta C_p}{\lambda}$ is approximately 1, one can state that the momentum equation is similar to the energy equation.
Since the Reynolds-number Re is low, which means mainly viscous and no turbulent transport, the heat transfer is mainly governed by conduction.

a We will first treat the heat transfer in a quasi-stationary concept and then add some corrections for turbulent heat transport.

The assumption are:

1. $\lambda_{plasma} << \lambda_{particle}$, so we have uniform particle temperature and gradients in the plasma.

2. Fouriers number $Fo = \frac{a.\tau}{R^2} >> 1$, with a = thermal diffusity, τ= particle heating up time, R = particle Radius, so a quasi stationary approach is allowed

The warming up of the particle is now calculated from the heat flux q_n, which follows out of the calculated temperature boundary layer, with the particle temperature as a boundary condition.
We first write time independent:

$$\nabla.q = 0 \qquad q = -\lambda\nabla T \qquad \text{or} \qquad \nabla.(\lambda(T).\nabla T) = 0$$

For argon, between 300 and 3000 K in good approximation holds:

$\lambda(T) = \gamma . \frac{\lambda_k}{T_k} . T + c$, where index k denotes roomtemperature.

So in spherical coordinates we get:

$$\frac{1}{r^2} (r^2 \lambda(T) \frac{\partial T}{\partial r}) = o \qquad \text{or} \qquad \frac{\partial}{\partial r} (r^2 (\gamma \frac{\lambda_k}{T_k} T + c) \frac{\partial T}{\partial r}) = 0$$

With boundary conditions $T(R) = T_{particle}$, $T_{(\infty)} = T_{plasma}$ we finally get for the heat flux to the particle:

$$q_n = \lambda(T_{part}). (\frac{\partial T}{\partial r})_{r=R} = \frac{\gamma}{2R} . \frac{\lambda_k}{T_k} (T^2_{plas} - T^2_{part}) + \frac{c}{R} (T_{plas} - T_{part})$$

Now we introduce time dependency by stating quasi stationary:

$\frac{4}{3} \pi R^3 \rho_p . c_p \frac{dT_{part}}{dt} = 4\pi R^2 q_n$, which is a Ricatti type ordinary differential equation, which we can linearise because $T_{plas} >> T_{part}$.

The solution reads: $T_p(t) = \frac{(T_{plas} + \frac{c}{\gamma \lambda_k} . T_k)^2}{\tau_{heat} . T_k} . t + T_k$

This of course holds up to the melting point of the particle.
To check if the quasi stationary approximation was right we solved the <u>time dependent energy equation</u> :

$$\frac{1}{T} . \frac{\partial T}{\partial t} = \frac{a}{r^2} . \frac{\partial}{\partial r} (r^2 (T + \delta). \frac{\partial T}{\partial r})$$

This equation has been solved numerically resulting in a time dependent boundary layer profile T(r,t). (see fig. 2)

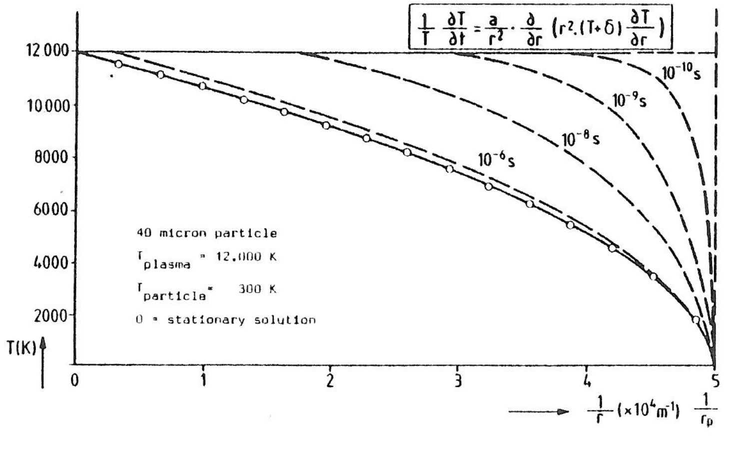


fig. 2

For 40 micron Mo-particles already within micro-second the boundary layer comes within 5% of the stationary one, while the total heat flux to the particle is just 13% more than the stationary one.
As on this time scale the particle temperature just increases 5 K we can savely ignore non stationary considerations.
The influence of convection in case of higher Reijnolds-numbers is taken into account by means of the Nusselt-number:

$Nu = 1 + (1 + Pe)^{1/3}$ where $Pe = \frac{2.v.R}{a}$ and $Pe = Re.Pr.$

The calculated heat conduction is multiplied by $\frac{Nu}{2}$ in order to get the total heat transfer.

b As far the theoretical calculation of momentum tranfer we take in first approximation a spherical particle in a Stokes flow in case of low Reijnolds numbers ($Re < 1$). The force F_w exerted on the particle is:
$F_w = 6\pi\eta\, R.\, (v_p - v_{gas})$. In case of higher Reijnolds numbers we describe the force with a dragg coefficient c_D:
$F_w = \frac{1}{2}\pi\rho\, (v_p - v_{gas})^2.\, R^2.c_D$. In our calculations we are for c_D the approximate expression:

$$c_D = \frac{24}{Re} \cdot \left| 1 + 0.1315.\ Re^{(0.82-0.05\ W)} \right|,$$ with $w = {}^{10}\log Re$. valid for $0.01 < Re < 20$.

In the computer program we start with one of the two momentum equations both in lateral and axial direction. We assume a known gas velocity and temperature and viscosity field of the plasma, according to Vardelle's[3] measurements carried out with a 29 kW Ar-H_2 plasma torch. The momentum equations result in a coupled set of second order differential equations which are solved by numerical integration.

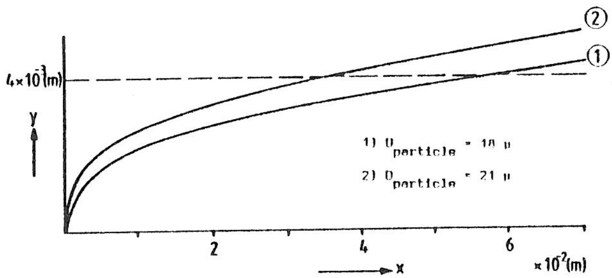
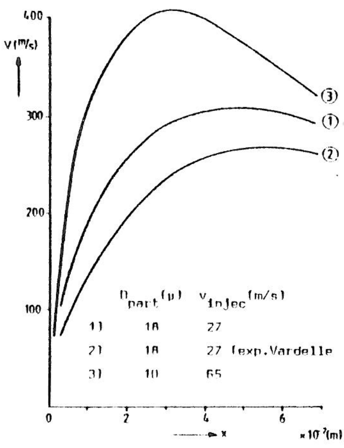


fig. 4 Orbit of an Al_2O_3 particle in the plasma jet.



In fig. 3 one can see the resultant axial particle velocity as a function of distance to the anode.
In fig. 4 one sees a particular orbit of an Al_2O_3 particle, injected perpendicular to the plasma axis.

fig. 3 Axial particle velocity of Al_2O_3 particles as a function of distance to anode plane.

4. RESULTS

- Besides the theoretical calculations of heat conduction and the orbit calculations we did a preliminary Laser-Doppler measurement on 60 micron Fe-particles injected in a 30 kW Ar/H_2 plasma torch as shown in fig. 5.

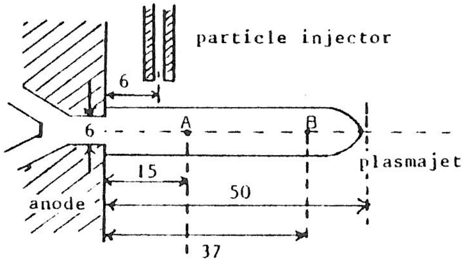


fig. 5 Actual plasma dimensions.

The axial particle velocities varried roughly between 40 and 100 $\frac{m}{s}$, going from A to B. Since so far we did not measure the gas velocity, no direct verification was possible with our numerical calculations.

- Furthermore we did a few preliminary electron density measurements by measuring the H_β half value width, not using abel inversion (see fig. 6)

The corresponding electron temperature calculated by asuming PLTE with a overpopulation factor [4] for the argon ground level of 2, varies from 14.700 K (center anode plane) to 12.500 K (25 mm out of anode plane on axis).

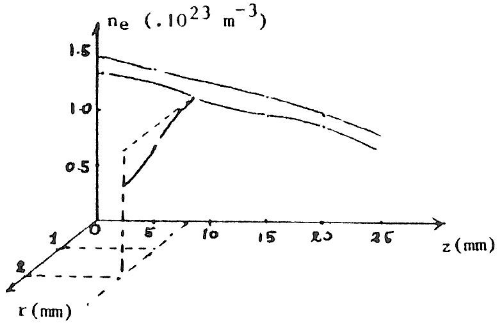


fig. 6 Spatial dependence of electron-density.

ACKNOWLEDGEMENT

We thank Dr. M. van Dongen for his advise given in calculating the heat conduction.

REFERENCES

(1) D. Kannapan and T.K. Bose, Physics of Fluids, 20 1668 (1977)

(2) H.R.Griem, " Spectral line broadening by plasmas" (Academic Press, London, 1974).

(3) M. Vardelle, Doctors thesis, University of Limoges, (1980).

(4) J. Leclair, D.C. Schram, Proc. 13^e ICPIG, 2 483 (1977)