MEASUREMENTS OF PARTICLE- AND PLASMA-VELOCITY IN A LOW-PRES-SURE PLASMA JET

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ABSTRACT:
Measurements of particle and plasma velocities as well as
turbulence intensities in a low-pressure plasma jet have been
carried out using a Laser Dual Focus Velocimeter (L2F). This
technique turned out to be well suited for this purpose. The
measurements also reveal the weak particle-plasma interac-
tions in a low-pressure plasma jet.

1. INTRODUCTION

Low-pressure plasma spraying (LPPS) has currently reached a
level of development which enables this technology to be used
for producing coatings on components subjected to high
stresses and strains. The advantages of the low-pressure
plasma spray technique over atmospheric plasma-spraying re-
side, among other things, in the improved mechanical proper-
ties of the coatings and in the possibility of depositing
reactive materials such as titanium /1 - 3/. However, it is
a fact that the coating properties attainable to date do not
always meet the requirements of aircraft and spacecraft con-
struction.

The reason for this is that the plasma spray technique has
been, and is being, largely developed empirically and that a
large number of parameters need to be taken into account /4
- 5/. Associated with this is a time-consuming, empirical
and hence uneconomic determination of parameters. Although
more recently some theoretical work has been undertaken on
the particle-plasma interactions in a low-pressure plasma jet
/6 - 8/, yust few experimental data are available on the
actual behaviour of the particles in a plasma jet under low-
pressure conditions /9/. For this reason, agreement between
the above-mentioned models and the actual behaviour of the
particles in a plasma jet is either still unsatisfactory or
unknown. Contactless methods for measuring plasma and parti-
cle velocities, e.g. Laser Doppler Velocimetry (LDV), are of
limited suitability because of, among other things, their
insufficient resolution and accuracy of measurement for small
particles (< 5 μm) / 10 /). For this reason, a proven method, namely the Laser Dual Focus Technique, which has been used for some time in the field of high-velocity fluid flows / 11, 12 /, is being applied at the University of Dortmund to measure particle and plasma velocities and to determine turbulence intensities in low-pressure plasma jets.

2. APPARATUS

2.1 Laser Velocimetry

Using the fringe model one can describe some features of the LDV. By constructive and destructive interference of the two laser beams a fringe pattern is generated as shown in fig. 1. When a particle passes through the probe volume a frequency modulation of the scattered light from particles moving through this region can be observed. Measurements in plasma-jets using this technique have been done by several authors / 10, 13, 14 /. The LDV is quite commonly used for relatively low-speed applications especially where an oblique forward scatter view for the receiving optical system is permitted. In such a case very good signal to noise ratios can be achieved because of the scattering properties of particles.

Introducing Laser Velocimetry for the study of flow fields in a plasma-jet is very difficult for various reasons. For a LDV a relationship exists between the number of fringes, the frequency of the output signal and the spatial resolution. For longer probe throws – as required for plasma-jet studies – and high speeds one usually works with fewer fringes and larger sample volumes. This reduces the illumination intensity, and only bigger particles generate a detectable signal. When the velocity of the plasma itself is to be measured, small particles are required in order to provide a response of reasonable accuracy. Flueckiger and Strazisar / 15, 16 / who have used special optimized Laser Doppler Velocimeters in high speed turbomachinery research estimated the minimum detectable particle size to be about 1.3 microns. The flare which is present in a plasma-jet and the necessity to use extrem narrow band interference filters / 14 / will lead to even higher values of the minimum detectable particle size.

Some time ago, when the Laser Doppler Velocimetry was applied to turbomachinery research, measurement problems rapidly became more difficult for the reasons mentioned before. To make measurements more easily obtainable other techniques were sought. Based on an idea by Tanner / 17 /, Scholz / 11 / designed a Laser Dual Focus Velocimeter (L2F) capable of measuring mean velocities, flow angles, turbulence intensities and Reynold’s shear stresses in lower turbulent fluid flows. The system has excellent wall and window flare rejection capabilities. The principle of the L2F is illustrated in Fig. 2. Two laser beam waists separated by a known distance form the sampling volume.

Usually the first one focal volume is interpreted as the start-spot and the second as a stop-spot. When a particle
traverses this optical gate, the flight time is a measure of the particle velocity because of the known distance of the two spots. The time intervals between successive start and stop pulses are measured and then further processed in a multichannel analyzer.

2.2 Experimental Conditions

The tests were carried out by using a commercial low-pressure plasma spraying system (LPPS). Its principal component is a working chamber which is evacuated to 0.2 mbar immediately before spraying. During spraying a pressure of 50 - 70 mbar is maintained. These conditions result in a considerable increase in the size of the plasma jet /18/. This type of unit is designed for d. c. arc powers of up to 120 kW for spraying high-melting point materials, too. The measurements using a L2F-Velocimeter equipped with an 300 mW argon-ion-laser were taken through the glass windows of the chamber doors. Three different guns (Fig. 3) with an Ar/He gas mixture were used. The operating conditions are summarized in Table 1.

3. RESULTS AND DISCUSSION

Fig. 4. shows the mean particle velocities for tungsten and Al2O3-particles measured by the L2F-Velocimeter at a chamber pressure of 1013 mbar and 50 mbar depending upon the geometries of the nozzles employed (see Fig. 3). It will be noted from Fig. 4 that the particle velocity is heavily dependent upon grain size and density of the various materials. The increase in particle velocity as a function of nozzle distance is relatively small in low-pressure plasma-spraying due to the reduction of the chamber pressure to 50 mbar compared with plasma-spraying under atmospheric conditions (1013 mbar). Moreover, as appears from Fig. 4, the acceleration of the particles in a low-pressure plasma jet is considerably less than under atmospheric conditions. There is minor influence of the different nozzle geometries on the maximum attainable particle velocity in a low-pressure plasma jet of Al2O3-particles. The photographic evaluation reveals that this result is probably due to the non-optimal pressure adjustment of the Laval-nozzles. The experimental results presented in Fig. 4 indicate that, for calculating the particle velocity as shown in /6 - 8/ it is necessary to make non-continuum assumptions in regard to the flow conditions in a low-pressure plasma jet. In order to measure the plasma velocity, extremely small particles had to be injected into the plasma torch. Kaolin particles with a mean size of 0.55 μm were applied. The size of these injected particles was examined with a Brookhaven Instrument BI-90 particle analyser using photon correlation spectroscopy. In view of the small grain size and density (2.6 g/cm³) of the kaolin it may be assumed that these particles behave substantially without inertia in the
plasma jet. Fig. 4 shows the results obtained from measurements of the kaolin particles in comparison with the measured velocities of the tungsten and $\text{Al}_2\text{O}_3$-particles in a low-pressure plasma jet, too. Under the operating conditions employed (see Table 1) the kaolin particles attain a maximum velocity of 907 m/s.

Fig. 5 shows the mean velocity and angular turbulence intensity of the particles, examined in the particular volume of measurement, in dependence upon the distance from the nozzle orifice for $\text{Al}_2\text{O}_3$-particles at a chamber pressure of 1013 mbar and 50 mbar as well as with different nozzle geometries. In addition, the behaviour of the kaolin-particles is shown. As already mentioned, the photographic evaluation indicated that the pressure adjustment of the Laval-nozzles (see Fig. 3) was not optimal (wrong counter-pressure in the working chamber). For that reason the expansion of the plasma jet already commenced at the nozzle exit.

The compression of the plasma which results from a cross-sectional constriction of the plasma jet and is associated with the transition from a supersonic to a subsonic rate of flow, was measured for Nozzle No. III at a distance of approximately 35 mm from the nozzle exit. This explains the behaviour of the small kaolin particles shown in Fig. 5. Thus, the minimum level of the velocity turbulence intensity of the kaolin particles is in good agreement with the constriction of the plasma jet whereas the angular turbulence intensity increases. In contrast to the behaviour of the small kaolin particles the larger $\text{Al}_2\text{O}_3$-particles are not measurably affected by the shock wave so that the velocity and angular turbulence intensity displayed in the forward section of the plasma jet remains relatively constant. Therefore, it can be concluded that the influence on the velocity and flight path of the particles exerted by the change in the plasma characteristics (e.g. pressure, density, temperature) occurring upon the transition from a supersonic to a subsonic rate of flow, is negligibly small at least in respect of the larger particles (approximately 50 $\mu$m). The higher angular turbulence intensity, which increases considerably at a distance from the nozzle orifice of approximately 150 mm, of the 54 $\mu$m $\text{Al}_2\text{O}_3$-particles sprayed with Nozzle No. III compared with those sprayed with Nozzle No. II is presumably due to the better focussing of the plasma jet achieved by Nozzle No. II. By contrast - and this was to be expected in view of the overall greater acceleration of the particles in an atmospheric plasma jet (see also Fig. 4) - the $\text{Al}_2\text{O}_3$-particles sprayed at a chamber pressure of 1013 mbar displayed significant increase in velocity turbulence intensity and a decrease in angular turbulence intensity over the entire length of the plasma jet (about 50 mm).

We are presently refining and completing these measurements in order to be able to present precise data on the behaviour of particles in a low-pressure plasma jet.
4. CONCLUSION

The good feasibility of the L2F-Velocimeter for measurements of particle- and plasma- velocities as well as turbulence intensities in a low-pressure plasma jet was demonstrated. The L2F method does not require coherence and is much less sensitive to window imperfections, fluctuations of the index of refraction and window contamination. The L2F overcomes the problem of a big sample volume by creating much smaller beam waists (10 to 15 microns) than typically used in laser Doppler systems (500 microns or larger). As a result, smaller seed particles, measurements closer to bulk surfaces and at higher velocities can be performed.

The insignificantly higher particle velocities measured at a chamber pressure of 50 mbar compared with a pressure of 1013 mbar point to a considerably reduced impulse and heat exchange in the low-pressure plasma jet. Furthermore, the results of the measurements show that a calculatory determination of the behaviour of particles in a low-pressure plasma jet necessitates non-continuum assumptions in regard to the flow conditions.
REFERENCES

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Table 1: Experimental operating conditions

Fig. 1: LDV-principle

Fig. 2: L2F-principle
Fig. 3: Nozzles for plasma guns

Fig. 4: Mean particle velocities in various plasma jets

Fig. 5: Turbulence intensities of particles in various plasma jets