INVESTIGATION OF RAYLEIGH INSTABILITY IN THERMAL PLASMA JET GENERATED BY PLASMA TORCH WITH EXTERNAL ANODE

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Abstract

Coherent oscillations with frequency in the range 20 – 80 kHz has been observed in thermal plasma jet close to the nozzle exit. From a phase shift of the oscillations along the jet, the wave phase velocity was evaluated. The phase velocity was substantially smaller than the plasma velocity. The dependencies of frequency, amplitude and phase velocity of the oscillations on parameters of plasma jet and on position in the jet were determined. The frequency of oscillations depends linearly on mean plasma velocity while the wavelength is independent of plasma velocity. The oscillations are interpreted as the Rayleigh instability in a plasma jet with velocity shear. The transition from the linear phase of the instability to nonlinear phase was observed in the course of wave propagation along the jet.

1. Introduction

Various types of fluctuations have been observed in thermal plasma jets. The fluctuations can be caused by several mechanisms like a movement of anode attachment along anode surface in a restrike mode, an interaction of a plasma jet with an anode jet or an interaction of plasma jet with ambient air. The design of the water stabilized plasma torch WSP 500 [1] with outer rotating anode positioned downstream of the nozzle enables an observation of the origin and evolution of instabilities in a relatively laminar part of plasma jet near the nozzle that is not influenced by the above mentioned mechanisms.

2. Experimental Set-up

The thermal plasma jet was generated by a water plasma torch with an external rotating anode positioned downstream of the torch nozzle. The diameter of the exit nozzle of the torch was 6 mm and mean plasma velocity at the nozzle was 1700 - 4300 m/s.

Fluctuations in the jet in the region between the nozzle and the anode attachment were observed using a linear array of six photo-diodes with maximum spectral sensitivity at 850 nm. The signals from the diodes were amplified by an amplifier with a bandwidth 30 Hz to 50 MHz. The diode array was positioned either parallel to the axial axis of the jet image or perpendicular to this axis, so it was possible to evaluate the phase shift of the oscillations in both, the axial and the radial directions. Recording of signals of the photodiode system was synchronized with a measurement of arc voltage. In addition, the image of the plasma jet was recorded by CCD fast shutter camera.
3. Experimental Results

Typical record of arc voltage and signals of three diodes, which picked up jet radiation from the region adjacent to the nozzle exit, is given in Fig. 1. The active surface of the anode was flush with the low edge of the nozzle orifice. At this situation the anode attachment is in a diffuse mode for which the arc voltage has no saw-tooth oscillations typical for a restrike mode of the attachment. It is obvious from Fig. 1 that almost sinusoidal oscillations of plasma radiation exist in the observed region of the jet. From the phase shift of oscillations from different photodiodes the phase velocity of oscillations was calculated.

Fig. 1. Curve of arc voltage $U_a$ and fluctuations of radiation $U_d$ emitted at different axial positions along jet at distances from the torch nozzle $z_{d1} = 1$ mm, $z_{d2} = 4.3$ mm and $z_{d3} = 7.7$ mm.

The frequency of these highly coherent oscillations depends on arc current (Fig. 2). The frequency of oscillations increases with arc current. It is also affected by a stability of water vortex in stabilizing chamber. Slight disturbances can take place in the water flow that cause changes in arc power balance. Because the power balance controls the exit velocity of plasma jet, all plasma flow characteristics are influenced by a water flow instability.

The dependence of phase velocity of oscillations on arc current is shown in Fig. 3. The phase velocity depends linearly on arc current. As plasma velocity changes also linearly with current [1], the phase velocity depends approximately linearly on plasma velocity. Simultaneous record of signals of 6 photodiodes (similar to Fig. 1) enables to find the dependence of velocity of sinusoidal waves on distance from the nozzle (Fig. 4) and the dependence of amplitude on the distance (Fig. 5).
The phase velocity slightly increases with distance from the nozzle to some maximum and then decreases. The maximum is close to the position of anode attachment. Thus phase velocity increases in a part of jet heated by an arc current passage, and decreases in a free jet.

It is seen in Fig. 5 that the amplitude of sinusoidal oscillations has maximum approximately at the same position as phase velocity. The maximum is related to the transition from linear phase of instability evolution into nonlinear phase. This can be seen from the evolution of Fourier spectra in Fig. 6. With increasing distance from the nozzle the second and third harmonic frequencies increase. The spectrum is also broadened to lower frequencies. It is caused by the distortion of waves due to interaction with anode attachment.
This phenomenon is strongly pronounced in the torch regimes with a restrike mode of anode attachment. These modes with characteristic saw-tooth oscillations were obtained if anode was slowed down and the distance from anode surface to the jet axis was increased [3]. The effect of anode restrikes is apparent even in the region upstream of the anode attachment (Fig.7).

4. Discussion

The observed oscillations are related to instability of plasma flow in the jet. Generally the flow instability in dc arc jets may be caused by fluctuations in an arc column, by interaction with electrode attachment regions of the arc or by hydrodynamic instability of plasma flow. As there was no relation between the observed coherent oscillations and arc fluctuations, we will analyze conditions for development of hydrodynamic instability. The critical Reynolds number quoted for the stability of cylindrical flows of liquid or gas is Re ~ 30 [4]. In our experiments the Reynolds number in the jet close to the torch exit was in the range 470 – 1140 that is substantially higher than the quoted value. Despite of the fact that electric current flows through the part of the jet just downstream the nozzle, the effect of magnetic field can be neglected, as mean free path of charged particles in the plasma is much lower than the Larmor radius. Thus we compared our results with conclusions of a simple theory of hydrodynamic instability.

Simple theory describing the origin of Rayleigh instability of flow with velocity shear [4] in a non-compressible fluids with triangle velocity profile gives a condition for wave instability in the form kD < 3.7 independently of flow velocity, where k is wave number and D is characteristic dimension of inhomogeneity of plasma flow. For waves with maximum increment the theory gives value kD = 2.4, again independently of flow velocity. It is
supposed that only the waves with maximum increment are generated. The frequency of the generated waves is approximately equal to $0.12v_{pl}/D$, where $v_{pl}$ is flow velocity of fluid.

We tested how the measured values correspond to conclusions of the theory. The flow of plasma can be considered as incompressible if terms related to compressibility are small. These terms are of order $v_{ph}/v_{pl}$ and $1/kD$, where $v_{ph}$ is phase velocity. The dependence of measured ratio and kD on plasma velocity is shown in Figs. 8 and 9. The ratio $v_{ph}/v_{pl}$ was calculated from values of $v_{ph}$ in Fig. 3 and from plasma velocities measured in [1]). Value of $k$ was evaluated from data presented in Figs. 2 and 3, for characteristic dimension $D$ the diameter of exit nozzle was taken. It can be seen that both $v_{ph}/v_{pl}$ and $1/kD$ are small and compressible terms in the equations can be neglected in the first approximation and thus conclusions of simple theory can be used. Experimental values of kD are only slightly dependent on plasma velocity and are not far from theoretical value $kD = 2.4$. The dependence of characteristic frequency on plasma velocity is given in Fig. 10. Theoretical dependence $f = 0.12v_{pl}/D$ is plotted by a dashed line. The coincidence of theoretical and experimental curves is good.

![Fig. 8. Ratio of phase to plasma velocity in dependence on plasma velocity.](image1)

![Fig. 9. Dependence of kD on plasma velocity.](image2)

5. Conclusions

The measured basic characteristics of waves generated in thermal plasma jet just downstream of the nozzle agree well with the results of simple theory of Rayleigh instability of fluid flow with velocity shear. There is relatively good agreement in the dependence of frequency on plasma velocity and qualitative agreement of the dependence of wavelength on plasma velocity. These facts support the conclusion that the observed coherent sinusoidal oscillations that develop close to the nozzle exit are generated by shear instability of Rayleigh type.
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References


