Plasma flow in an argon cascade arc

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PLASMA FLOW IN AN ARGON CASCADE ARC

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Introduction

Flowing thermal plasmas are frequently used e.g. in welding, cutting, plasma deposition and testing materials at high temperatures. In most of the applications the geometry is complex. In the cascade arc the argon plasma flows through a straight circular channel with a constant area. The study of the flow and of the plasma properties are facilitated thereby. Velocities in the order of 1000 m/s and mass flows of a few grams per second can be reached by applying a pressure difference of a few bar over the arc. The ohmic heating of the plasma also increases the flow speed. In this work a model is presented that shows the influence of the pressure, the ohmic heating and the thermodynamic properties of argon on the flow. Results of measurements will be given.

Experimental set-up and diagnostics

The cascade arc (fig. 1) consists of a set of water cooled copper plates, thick 1.6 mm. In the middle of the package a plate of 7 mm thickness is mounted in order to installate a pressure transducer. The central holes of the plates, which are insulated from each other with a spacing of 0.28 mm, form a circular plasma channel with a diameter of 5 mm and a length of 50 mm. A current between 40 and 100 A is provided by a D.C. power supply. Four anodes and four cathodes of tungsten are used, each with a stabilizing resistor in series. The flow is being made by imposing a pressure up to 4 bar at the cathode side of the arc. At the anode side a free expansion to atmospheric pressure is possible.

The measured quantities are the pressure on the cathode side and half-way the channel, the mass flow through the arc and the voltages of the plates. From these voltages the local electric field in the arc can be derived.

The one-dimensional model

Former experiments [1] showed that atmospheric argon plasmas without flow are close to Local Thermodynamic Equilibrium (LTE). The flow will have some influence but LTE densities of electrons, ions and atoms calculated at a given temperature can be used. Assuming that the differences in the drift velocities of the heavy particles can be neglected, the plasma flow can be treated gasdynamically, using the equilibrium properties of argon. In particular the specific enthalpy is needed, see fig. 2. Consider the flow to be one-dimensional, stationary and through a channel with constant area. The laws of conservation of mass, momentum and energy are in differential form:

$$d(\rho u) = 0 \qquad (1)$$

$$\rho u du + dp = -\frac{\rho u^2}{2} 4f \frac{dx}{D} \qquad (2)$$

$$u du + dh = dq \qquad (3)$$

with ρ : mass density,
u : flow speed,
p : pressure,
f : friction coefficient,
x : space coordinate along the arc,
D : diameter of the plasma channel,
h : specific enthalpy,
q : added energy per unit mass.

Furthermore we need the equation of state:

$$p = \rho RT(1+\alpha) \qquad (4)$$

with R : specific gas constant for argon,

T : temperature,

α : degree of ionization $(n_e/(n_e+n_a))$.

With the assumption of LTE the specific enthalpy and the degree of ionization are only functions of temperature and pressure. The differential dh can be written as

$$dh = c_p dT + c_T\, dp$$

in which $c_p = \{\frac{dh}{dT}\}_p$ and $c_T = \{\frac{dh}{dp}\}_T$

The degree of ionization is a few percent and will be neglected. The ohmic heating is given by

$$dq = \frac{IE\, dx}{\rho u A}$$

with I : electric current,

A : area of the channel.

Combining the above equations gives the following system of first order differential equations in the variables p, u and T:

$$\frac{1}{p}\frac{dp}{dx} + \frac{1}{u}\frac{du}{dx} - \frac{1}{T}\frac{dT}{dx} = 0 \qquad (5)$$

$$\frac{dp}{dx} + \frac{pu}{RT}\frac{du}{dx} = -\frac{2pu^2}{RT}\frac{f}{D} \qquad (6)$$

$$c_T\frac{dp}{dx} + u\frac{du}{dx} + c_p\frac{dT}{dx} = \frac{RT\cdot IE}{puA} \qquad (7)$$

The equations of this system are dependent when the Jacobian equals zero, which is the case for

$$u^2 = \frac{c_p RT}{c_p + c_T\cdot\frac{p}{T} - R} = \gamma RT \qquad (8)$$

γ is the ratio of c_p and c_v, the specific heat capacities at constant pressure respectively constant volume. For cold (not ionized) argon $\gamma = 5/3$ and for higher temperatures it becomes smaller and reaches values almost down to one. When equation (8) is fulfilled, the flow speed of the plasma equals the speed of sound (Mach number M=1). In a channel with constant area M=1 only can be reached at the end of the duct [3]. For M<1 the pressure in the end plane is one bar (atmospheric pressure). For M=1 the pressure can become larger than one bar and the transition to atmospheric pressure is reached by one or more shock waves. The mass flow $\phi = \rho u A$ calculated for M=1 and p=1 bar is the minimum value for which the flow becomes sonic. For a temperature of 11000 K this value is 1.3 g/s.

To consider the effects of friction and ohmic heating we rewrite the equations (5)-(7) to:

$$\frac{dp}{dx} = \frac{1}{N}\{-2pu^2(u^2+c_pT)\frac{f}{D} - \frac{uRTIE}{A}\} \qquad (9)$$

$$\frac{du}{dx} = \frac{1}{N}\{2u^3(c_pT+c_Tp)\frac{f}{D} + \frac{(RT)^2IE}{pA}\} \qquad (10)$$

$$\frac{dT}{dx} = \frac{1}{N}\{-2u^2(u^2-c_Tp)\frac{f}{D} + \frac{(RT-u^2)RT^2IE}{puA}\} \qquad (11)$$

in which $N = u^2(RT-c_pT-c_Tp) + c_pRT^2$ and equals the Jacobian of system (5)-(7) multiplied by $-uRT^2$. We notice the following changes in pressure, speed and temperature in the positive x-direction:

a) the pressure decreases both by friction and ohmic heating,

b) the speed increases both by friction and ohmic heating,

c) the temperature decreases by friction and increases by ohmic heating (the latter not for $u^2 > RT$).

Experimental results

The result of a typical measurement is given in fig. 3. Initially the total arc is at a pressure of one bar. The high pressure valve is opened and the pressure on the cathode side of the arc goes up until a stationary situation is reached. After one second the valve is closed and the old situation is restored. During the pressure pulse the electric field increases. The voltages of the plates, relative to the plate at x=15 mm, are given in fig. 4, both with and without flow. Because the electric conductivity does not vary much with pressure at temperatures between 50000 and 15000 K and pressures betweeen 1 and 4 bar, the local temperature can be derived from the rise in the electric field during the pressure pulse. The averaged current density is constant, so an increase in the electric field directly gives the decrease in the electric conductivity and from that the decrease in temperature. The results are given in fig. 5. The pressure difference over the arc is one bar. The mass flow is 2.25 g/s so a sonic flow is reached at the exit of the channel. During the flow fluctuations in the voltages are present. For all the plates the magnitude of the fluctuations is about the same and a frequency of 8.5 kHz is dominant. A fase difference between the fluctuations at successive plates is present. In the pressure measured at the inlet side of the arc the 8.5 kHz fluctuations also occur but the magnitude is smaller than one percent of the total pressure.

[1] C.J. Timmermans, An investigation of pulsed high density plasmas, Ph. D. thesis, Eindhoven University of Technology, Eindhoven, The Netherlands, (1984).
[2] J. Aubreton, Private communication.

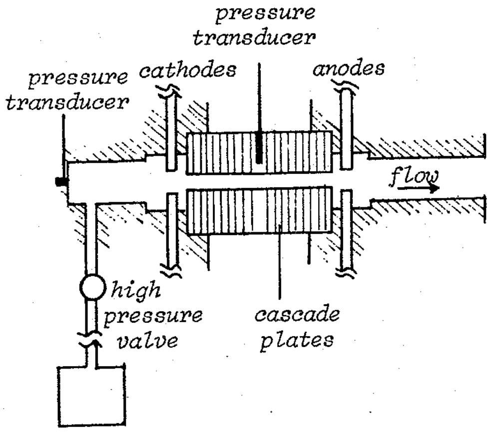

Fig.1. Overall view of the cascade arc.

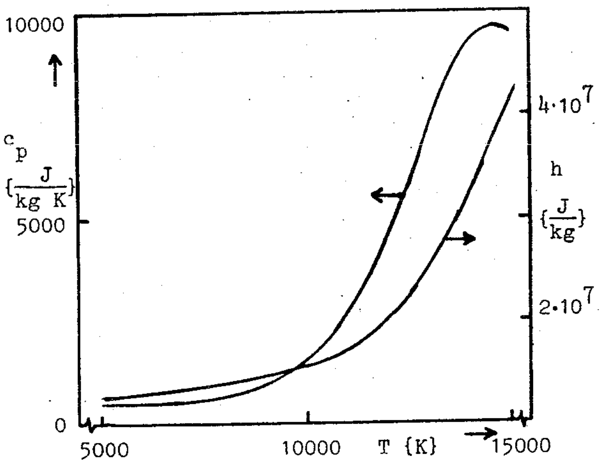

Fig.2. Thermodynamic properties of argon at one bar.

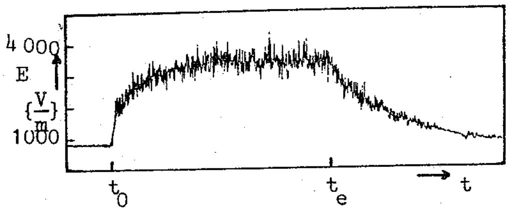

Fig.3. The local electric field in the arc during a pressure pulse.

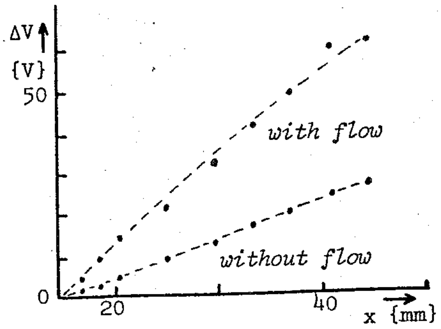

Fig.4. Voltages of a number of plates with respect to the plate at $x=15$ mm.

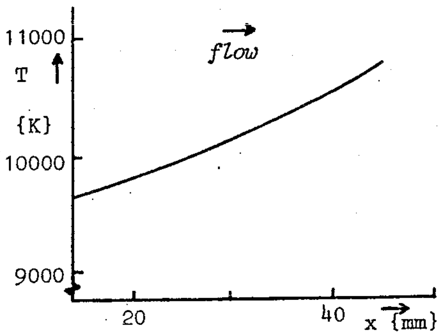

Fig.5. Local temperatures in the flowing arc determined from the rise in electric field.