MHD arcjet onset studies

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Abstract: The phenomenon of onset in MHD arcjets is studied. An earlier solution procedure is combined with an onset criterion to obtain the onset boundary curves for hydrogen and argon. The onset boundary curves are in qualitative agreement with experimental results. It is found that the engine-specific impulse at onset can be increased by increasing the propellant low-temperature electrical conductivity. For plasma temperatures in the range 8000–12000 K, it is predicted that a higher specific impulse at onset should be obtained for hydrogen than for argon.

1 Introduction

The MHD arcjet is an electric space-propulsion device capable of attaining a high specific impulse [1]. For a given propellant mass flow rate in the arcjet, the specific impulse increases with the total arc current [2]. Operation at higher total currents is therefore desirable. However, it is found experimentally [2] that, when the total current (for a given propellant mass flow rate) exceeds a certain value, unsteady conditions, termed 'onset', develop in the plasma, leading to a rapid erosion of the electrodes. Instabilities in the plasma and fluctuations in the arc voltage also arise. Sample values are an onset current of 23 kA for an argon propellant mass flow rate of 6 g/s [2]. Studies of onset phenomena are therefore important.

The author has recently investigated [3, 4] current density distributions in MHD arcjets by solving the electromagnetic equations for given aerothermodynamic input variables. The solution procedure already developed can be used with an onset criterion to obtain onset boundary curves. The objective in this work is (i) to obtain and compare the onset boundary curves for hydrogen and argon, and (ii) to examine ways of increasing the onset limit on specific impulse.

2 Arcjet geometry, grid details and solution procedure

A typical arcjet geometry is shown in Fig. 1. Propellant is introduced into the arcjet through inlet ports in the dielectric at the left. For this study, it is assumed that the propellant on entry to the arcjet is electrically conducting. This can be achieved by, for example, (i) a separate ionising discharge, (ii) the introduction of conducting seed material in the propellant, or (iii) preheating the propellant in a first stage conventional rocket engine. In the arcjet interior, the self-induced magnetic field and the current density bring about electromagnetic acceleration of the propellant.

A grid has to be generated in the arcjet interior to permit the numerical solution of the electromagnetic equations. Because of the axisymmetric nature of the problem (there is no dependence of any variable on the azimuthal co-ordinate), a two-dimensional grid is sufficient. For grid generation, the arcjet interior is divided into three regions. Region 1 is defined by \( b \leq z \leq c \), \( 0 \leq r \leq r_1 \), on which a uniform rectangular grid containing 76 points is generated. Region 2 is defined by \( 0 \leq z \leq c \), \( r_1 \leq r \leq r_2 \), on which a uniform rectangular grid containing 341 points is generated. Region 3 is defined by \( c \geq z \geq \) anode flared boundary \( r > r_2 \), on which a uniform triangular grid at the anode flared boundary and a uniform rectangular grid elsewhere are generated. Region 3 contains 276 grid points.

The details of the solution procedure are described elsewhere [3, 4] and will not be repeated here. Briefly, the solution procedure assumes a given aerothermodynamic field and solves for all the electromagnetic variables. The aerothermodynamic field and the electromagnetic variables are assumed steady (i.e., not time-dependent). Typical values of input parameters are given in Table I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degree of ionisation</td>
<td>1.0</td>
</tr>
<tr>
<td>Anode, cathode potentials</td>
<td>\pm 15 V</td>
</tr>
<tr>
<td>a</td>
<td>1.4 cm</td>
</tr>
<tr>
<td>b</td>
<td>2.4 cm</td>
</tr>
<tr>
<td>c</td>
<td>6 cm</td>
</tr>
<tr>
<td>( r_1 )</td>
<td>0.2 cm</td>
</tr>
<tr>
<td>( r_2 )</td>
<td>0.7 cm</td>
</tr>
<tr>
<td>( f_1 )</td>
<td>3 cm</td>
</tr>
</tbody>
</table>
In principle, the degree of ionisation must be obtained from a simplified Saha equation, but it is here assumed to be unity for simplicity.

3 Onset criterion and the onset boundary curves

It is proposed in this work that the first occurrence of onset can be predicted from solutions of the steady electromagnetic equations by means of the following criterion: onset first occurs when the normal component of the current density vector first becomes locally zero anywhere on the cathode or anode surface; i.e. first occurrence of

\[
\begin{align*}
  j \cdot n_c &= 0 \text{ anywhere on cathode} \\
  j \cdot n_a &= 0 \text{ anywhere on anode}
\end{align*}
\]

defines the occurrence of onset.

Here \( j \) is the current-density vector obtained by solution of the steady electromagnetic equations and \( n_c, n_a \) are local normal unit vectors on the cathode and anode surfaces respectively. Eqn. 1 can be used to obtain the onset boundary curve, i.e. the curve separating the region of onset from the region of no onset. The procedure for obtaining the onset boundary curve requires that each input parameter be varied systematically in turn until eqn. 1 is satisfied. The sets of all input parameter values that satisfy eqn. 1 represent the onset boundary curve. The input parameters that determine the current-density vector are the geometrical factors \( a, b, c_1, r_1, r_2 \) and \( r_3 \), the anode-cathode potential difference, the plasma temperature, density, and velocity, and the propellant type. The author was able to satisfy eqn. 1 only by varying the values of plasma temperature and velocity. Variations in the other parameters did not result in eqn. 1 being satisfied. It is therefore appropriate to present the onset boundary curve with plasma velocity and temperature as axes. Fig. 2 shows the onset boundary curves obtained for hydrogen and argon propellants.

![Fig. 2 Onset boundary curves for hydrogen and argon propellants](image)

4 Results, discussion and conclusions

It is necessary to note that the co-ordinates of Fig. 2 represent the two possible forms of propellant energy, namely ordered (plasma velocity) and thermal (plasma temperature). With this in mind, Fig. 2 can be interpreted in the light of experimental observations that, for a given mass flow rate, as the total arc current is increased, onset occurs beyond a certain point. The case of increasing arc current for a given mass flow rate is depicted by the arrow in Fig. 2. The co-ordinates of any point on the arrow represent the relative proportions in which plasma energy is distributed between ordered motion and thermal energy at that point. The slope at any point on the arrow represents the relative proportions in which any additional input energy from the arc is distributed between ordered motion and thermal energy of the plasma at that point. The arrow is shown here as a straight line, but in general can be any curve with increasing co-ordinate values and starting at a point corresponding to the energy of the propellant at the inlet to the arcjet. The arrow will be different for different propellants, and will have larger slopes for propellants with larger electrical conductivity. The detailed shape of the arrow is also experiment-dependent, but the important point is that both its co-ordinates must increase in value if it is to represent the case of increasing arc current for a given mass flow rate. It should be clear from the above that the arrow will in general intersect the onset boundary curve resulting in the occurrence of onset. Thus Fig. 2 is in qualitative agreement with experimental results.

A fundamental objective is to increase the engine-specific impulse at onset. Since the engine-specific impulse is directly proportional to the plasma velocity, it is desirable that the arrow intersect the onset boundary curve at as high a velocity as possible. It can be seen from Fig. 2 that, the higher the slope of the arrow, the larger will be the velocity (and specific impulse) at which the arrow intersects the onset boundary curve. Higher slopes of the arrow imply that larger fractions of the input arc energy must be distributed to ordered motion (plasma velocity) than to thermal energy (plasma temperature). This requires that the propellant low-temperature electrical conductivity be increased. Thus, this work predicts that the engine-specific impulse at onset can be increased by increasing the low-temperature propellant electrical conductivity. This can perhaps be achieved by seeding the propellant with a conducting material.

Fig. 2 shows some differences between the onset boundary curves for hydrogen and argon. To qualitatively compare the onset behaviour of the two propellants, it is necessary to compare the respective points of intersection of two arrows of increasing arc current (one for hydrogen, the other for argon) with the respective onset boundary curves. General conclusions are difficult to obtain. However, in the temperature range 8000-12000 K, hydrogen plasma electrical conductivity is roughly twice that of argon. Consequently a higher specific impulse at onset should be obtained for hydrogen than for argon at these plasma operating temperatures.

5 References

1. TAHATA, J.; ‘Electric propulsion activities in Japan’. 17th International Electric Propulsion Conference, 1984, IEPC, pp. 84-95