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16. Abstract Tests for determining the influence of an axisymmetric EM field on the characteristic velocity of an arc jet are presented. The experimental set up is briefly described. Tests were performed with rotation induced by the centrifugal and magnetic fields in the same sense. The fuels used were He and N2 and the results are discussed. It is found that by variation of the induction current, and arc jet strength, the behavior is essentially determined by the shape of the cathodic and anodic blobs on the electrodes together with their movement under the combined effect of the aerodynamic and magnetic fields. In view of the different characteristics of He and N2 in respect to the dissociation heat and ionization, it is expected that the regime of the arc jet when used with H2 fuel will be similar to that with He.

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AXISYMMETRIC ELECTROMAGNETIC FIELD INFLUENCE ON THE CHARACTERISTIC VELOCITY OF AN ARC-JET** /1*

By Mario Oggero and Dario Gennuso

1 INTRODUCTION

The propulsive characteristics of an arc-jet depend on the quantity of heat introduced into the propellant gas and the efficiency of transformation of thermal to kinetic energy in the expansion nozzle. For a given electric power applied, the former depends on the heat exchange between the heat source (the electric arc) and the surrounding gas; the latter is mainly determined by the eflux modality and the heat transmission from the gas to the surrounding walls.

In practice, during the preparation of electrothermal propellers one inevitably has to reach a compromise between optimizing the propulsive performance and the system's overall yield: in order to limit heat losses at the walls - which in addition to causing a decrease in yield, can be the cause of electrode erosion - strongly non-uniform jets are often acceptable, with steep transverse thermal gradients, such that the walls come in contact only with relatively cold gases.

Such conditions occur when a centrifugal field is created inside

* Numbers in the right margin indicate foreign pagination

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the chamber that forces the arc to adopt an axial position inside the propeller, keeping it away from contact with the walls.

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However, in this manner the heat exchanged between the arc and the gas is considerably reduced and the mean eflux velocity becomes noticeably smaller than that corresponding to a uniform jet of the same mean enthalpy.

In order to improve the heat exchange between gas and arc without losing the advantages of stabilization, in readying arc-jets for propulsive applications one often resorts to hybrid solutions, in which an axisymmetrical electromagnetic field is superimposed over the centrifugal field, to rotate the arc in a plane transverse to the propeller's axis.

Considerable experimental work has already been performed by the main research laboratories on the conditions for optimization, using the independent variables available (electromagnetic field, vortex, electrode and chamber shape) to obtain the best compromise between propulsion performance and overall yield. However, a general solution to the problem is extremely complex, and hence in practice to date, only specific solutions have been arrived at, each tied to the specific propeller under examination.

The experiments that have been performed for several years at the Turin Polytechnic's Institute for Aircraft Machines and Engines, with CNR financing, have also been of this type. In this note, in particular, we submit research on the influence of the stabilizing magnetic field on an arc-jet's characteristic velocity, using various working gases and flow rates. This effort is part of an overall program with the objective of studying the main parameters that affect the performance of these propellers near optimum operating conditions, with the purpose of obtaining valid indications to establish the design criteria to be used in possible space propulsive applications.

2 TEST MODES /3

The tests were performed using the facilities already used in previous experiments [1, 2]*, shown in Figure 1**, including also indications regarding the main instrumentation used.

Since previous experiments had shown that the arc-jet's best operating conditions, from the point of view of electrode consumption and operating stability, were obtained working with arc currents of 200-250 A, the investigation of the influence of the magnetic field was limited to the first of these values. For similar reasons the gas flow rates were limited to the range of practical interest, from the point of view of proper functioning.

In regard to the combination of electromagnetic and aerodynamic forces, all tests were performed maintaining agreement in the direction of rotation induced by the centrifugal and the magnetic fields, because such an arrangement is usually better suited to regularity of operation and electrode duration. The case of forces acting in opposing directions was studied only in isolated instances, and such tests confirmed the criticality of the practice.

The propellants used were helium and nitrogen: the latter was chosen with the awareness that while it is of no propulsive interest, it is diatomic as is hydrogen, has fairly high arc voltages and - again as hydrogen - high heats of dissociation

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* Numbers in square brackets indicate bibliography

** Figures will be found at the end of the article

and ionization, without, however, the dangers of flammability. This, bearing in mind that the experimental facility is not yet completely ready for tests with hydrogen. To render the tests more uniform, all experiments were performed in the same modality, operating at constant gas flows and currents, and /4
using the electromagnetic field as the variable. Some tests were also performed keeping the field and the current constant and varying the gas flow rate. As we shall see below, the results of these tests were the same as those obtained in the earlier mode only for nitrogen: for helium, the differences between the two modalities were very large, occasionally.

All experiments were preceded and followed by a control test with cold gas, to verify the stability with time of the arc-jet's geometric characteristics (with particular attention to the nozzle's inner contour).

3 PROCESSING MODE

The results of the experiments were classified on the basis of the parameter normally called "characteristic velocity" (V^*) in rocket technology, and defined by

$$V^* = \frac{P_c A_t}{\dot{m}}$$

where V^* = characteristic velocity (m/sec)

P_c = pressure in the chamber, at the reference section (kg/m^2)

$\dot{m}$ = propellant mass flow (kg·s^2/m)

At = narrow section of the nozzle (m^2)

In the field of chemical endoreactors, the characteristic velocity is used as an indicator of combustion efficiency and has the physical meaning of an explicit function of the combustion temperature, the propellant's molecular weight and the ratio of the specific heats "k": /5

$$V^* = f(k)\sqrt{\frac{RT}{M}}$$

i.e., assuming uniform pressure in the chamber and uniform eflux through the nozzle.

In the specific case of the arc-jet under examination, the pressure in the chamber varies radially, due to the vortex; the tangential component of the velocity causes a partialization of the throat section, near the nozzle, and in addition, in the nozzle area considerable heat exchange takes place at the walls.

Hence the parameter V* does not have an explicit meaning, but rather becomes a complex function of the gas' thermodynamic state, in which it is practically impossible to distinguish the part strictly due to the temperature from that determined by the vortex, or that caused by the inductive forces (this portion is much smaller).

In spite of this difficulty of interpretation, we thought it of interest to examine this parameter, since at constant flow - and hence, as a first approximation, at constant vortex intensity - the change in V* as a function of the other parameters provides a direct indication of the influence of the parameters themselves on the jet's characteristics and in particular, on its uniformity and its temperature.

4 RESULTS OBTAINED

The test results, elaborated in terms of V*, are shown in the diagrams of Figures 3 through 8, as a function of the electromagnetic induction, and in Figures 9 through 12 as a function of the gas flow.

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Since the results obtained for the two gases follow a somewhat different course, we shall discuss them separately.

4.1 Tests with nitrogen (Figures 3, 4, 5, 9, 10)

The experiments performed in a flow rate range from 0.06 to 0.45 g/sec showed a characteristic behavior for all values studied: when the stabilization changes from being due only to the vortex to being composite, there is a sudden increase in the characteristic velocity and correspondingly, in the arc voltage. The two parameters attain maximum values for very low induction values and then slowly decrease continuously as the latter increases.

The phenomenon is more marked at low flow rates, for which on the one hand the degree of ionization is greater and on the other, the centrifugal field is less intense, and hence the arc's sensitivity to the magnetic field is higher.

For a constant induction, the characteristic velocity decreases as the flow rate increases, in accordance with the gas' lower enthalpy. The curve, however (see Figure 3) is not continuous, but presents a singularity at the flow rate of 0.2 g/sec.

In correspondence with that point the arc-jet's behavior is anomalous: the arc is stable only for the highest induction values, while for the lower ones two operating conditions exist, apparently both stable, with different arc voltage and characteristic velocity values. The higher values are usually obtained when the flow rate of 0.2 g/s is set, starting from higher values; the opposite is true when that value is reached starting from lower flow rates; occasionally, however, a sudden switch can occur from one situation to the other, regardless of starting flow rate, and even repeatedly in the course of the same test.

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4.2 Tests with helium (Figures 6, 7, 8, 11, 12)

The behavior of helium differs, in some respects, from that of nitrogen: in the flow rate range explored (from 0.03 to 0.14 g/s) the characteristic velocity and the arc voltage progressively increase as the magnetic field applied increases, until the asymptote is reached, practically, for values of $2 \cdot 10^{-2}$ W/m^2, for all gas flows.

Especially for the lower gas flows, the dispersion of the values is quite large and in addition they are strongly affected by the test modality. As was already mentioned, the arc-jet's behavior differs, depending on whether the operation is at constant flow rate, with the induction varying, or whether the gas flow is varied at constant induction. In the latter case, in addition, "hysteresis" phenomena can be observed, similar to those observed for nitrogen at 0.2 g/sec, with different values of arc tension and characteristic velocity depending on whether the gas flow is being increased or decreased.

5 ANALYSIS OF THE RESULTS

The total of the results mentioned above, even with the gaps pointed out, allows for some general considerations that can be summarized as follows:

5.1 Tests with nitrogen gas

In the tests with nitrogen, the sudden increase in voltage and characteristic velocity that accompany the application of the magnetic field seem to indicate that the effect of the electrodynamic forces on the ionized gas column seems related not so much to the corresponding forces applied by the electrodynamic fields (because in that case we should observe the same effects for constant force ratios, when the gas flow /8
is varied), as it is to some action on the points of contact of the arc with the electrodes.

More in particular, we could hypothesize that the electromagnetic induction determines a sudden rotation of the cathodic spot (which is never perfectly axial, as can be seen indirectly, from the residual marks on the electrode) and the circle of anodic spots, where the arc touches.

In the specific case of nitrogen, with its high ionization potential in addition to its high heat of dissociation, the dimensions of the cathodic spot are very narrow, and the sudden displacement of the arc's point of contact to an area where the electrode is practically cold, determines a sudden increase in the thermoelectron extraction voltage. Correspondingly, the nozzle eflux is disturbed by the arc movement, while there is a local increase in the gas' internal heat exchange: this causes the sudden variation in the characteristic velocity we pointed out.

When the inductive forces increase at constant gas flow, the velocity of rotation of the arc's points of contact progressively increases and the cathodic and anodic spots become uniformly distributed over the entire electrode surface.

Under these conditions the arc's contact surface becomes ring-shaped and the emission conditions become more regular: as a consequence there is a decrease in the arc's voltage. The charcateristic velocity follows the course of the voltage and undergoes a gradual decrease towards the initial values, without magnetic field. This behavior is probably related to the fact that the arc's fast movement partially cancels the vortex' protective effect, aiding the loss of heat to the walls, due to which the jet's temperature gradually decreases. /9

We should mention, in this regard, that the appearance of the jet at the discharge point, in the presence of the magnetic field, is different from that with vortex stabilization only: in the first case the exiting jet is not very luminous and nearly transparent, rather short and with a characteristic rustling noise; in the second, in contrast, the jet is long, very luminous, sometimes with a whistling noise.

As the flow rate increases, the effects of the aerodynamic forces progressively tend to attenuate those of the magnetic field, until finally, at a value of $G = 0.7$ g/sec, the arc voltage and characteristic velocity remain practically constant when the induction is varied.

5.2 Tests with helium

In addition to their considerable scatter, the results obtained with helium follow a course noticeably different from that with nitrogen.

These differences in behavior can be explained in terms of the different ratio of inductive and centrifugal forces existing between the two gases: with helium, in fact, the dimensions of the ionized column are much larger, with probably higher temperatures. Consequently, the geometry of the arc's points of contact on the electrodes will be different. In particular we may assume that the cathodic spot completely covers the electrode tip and that at low flow rates the arc occupies practically all areas of the nozzle and thus, the electromagnetic forces would not induce any significant variations in the geometry of the arc itself. At higher flow rates the vortex tends to limit the arc column and in that case induction, favoring heat exchange with the surrounding gas, produces a progressive increase in the voltage.

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Since the ionized column directly affects the eflux cross-section, its movements translate into variations in the conditions of eflux from the nozzle and consequently, into variations in the characteristic velocity.

In operations with helium such variations do not readily correlate with the magnetic field. In a general way the characteristic velocity increases with increasing induction, but as we have said, often "hysteresis" conditions are observed, due to which the result changes depending on whether operation is at constant flow rate and variable induction, or constant induction and variable flow rates.

Such a behavior can be explained assuming that because of the low flow rates involved (which cause a rather modest aerodynamical disturbance), the cathodic and anodic spots tend to maintain their original positions and therefore the thermoelectron extraction voltage and the arrangement of the ionized column could differ, for the same conditions. A similar phenomenon is found also for nitrogen, for the lowest flow rates and in particular, for the value 0.2 g.sec: also in this case there apparently exist two sets of apparently stable conditions that depend only on the test modality.

6 CONCLUSIONS

The tests performed with nitrogen and helium have shown that the operation of the arc-jet under consideration is sensitively affected - at constant gas flow and arc current - by the presence of an axisymmetric magnetic field, which induces variations either in the propeller's electrical behavior (arc voltage), or on the thermodynamic characteristics (overall temperature distribution and their absolute values) of the exiting jet.

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With respect to the latter, the tests have provided only an overall indication: while the measurements performed do not allow a separate evaluation of individual phenomena, they have pointed out the ranges in which these phenomena are affected by the presence of applied magnetic fields, and the magnitude of the variations induced.

We can deduce, from an analysis of the results obtained - even though they are limited to the ranges of gas flow, current and magnetic induction examined - that the behavior of the arc-jet operated either with nitrogen or helium, is ultimately determined only by the shape characteristics of the cathodic and anodic spots on the electrodes, and their movement under the effect of the combined aerodynamic and magnetic fields. Readily ionized gases (monoatomic gases) should exhibit a behavior similar to that of helium, and conversely, gases with high heats of dissociation and ionization should behave like nitrogen. With such hypotheses it should be remembered that operation with hydrogen will be much more like that with nitrogen, than that with helium.

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1 Oggero, M. and Bertolo, C., Impianto per le prove con arcojetti [Facilities for arc-jet testing], Istituto di Macchine Pubblicaz. No. 73, May 1967

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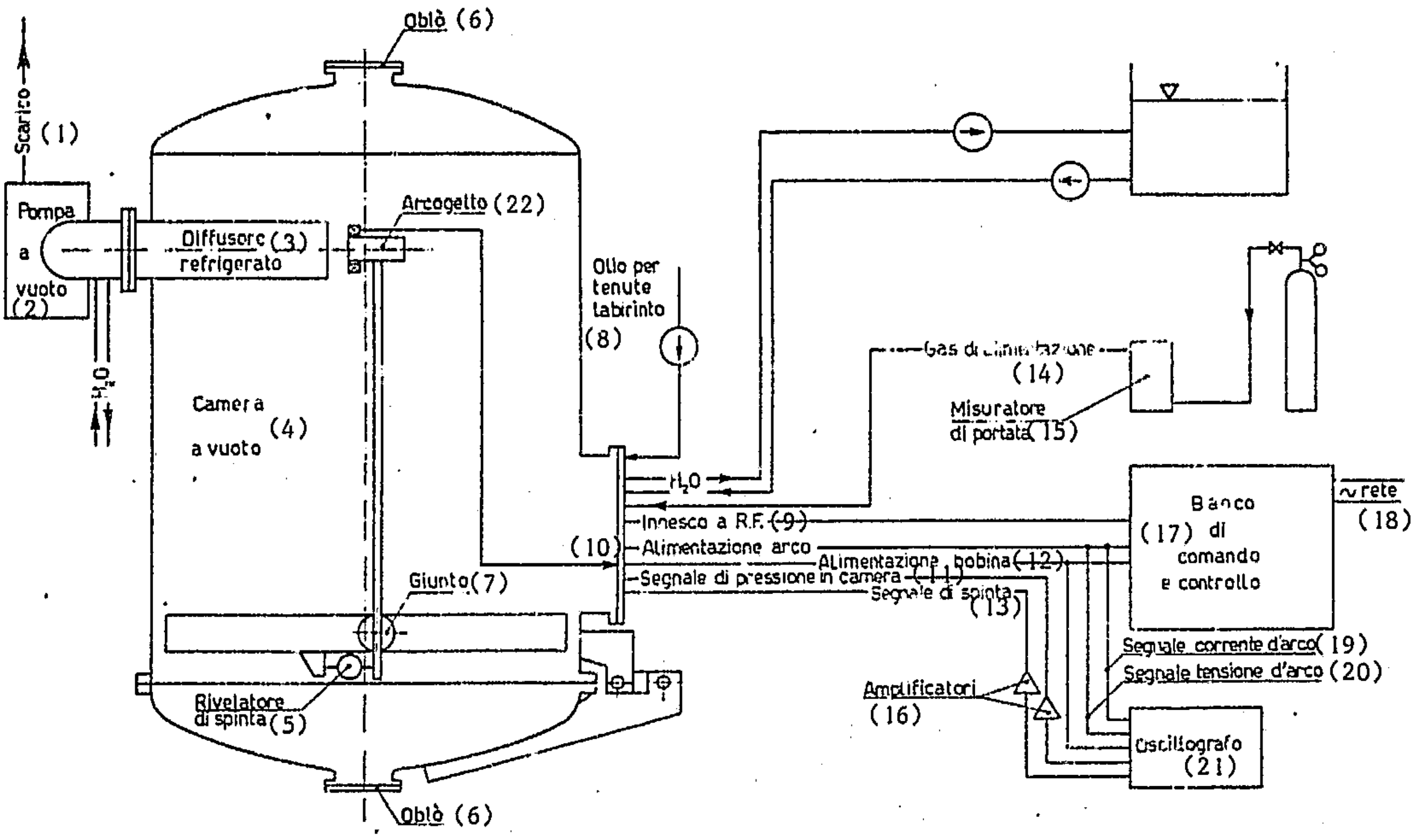
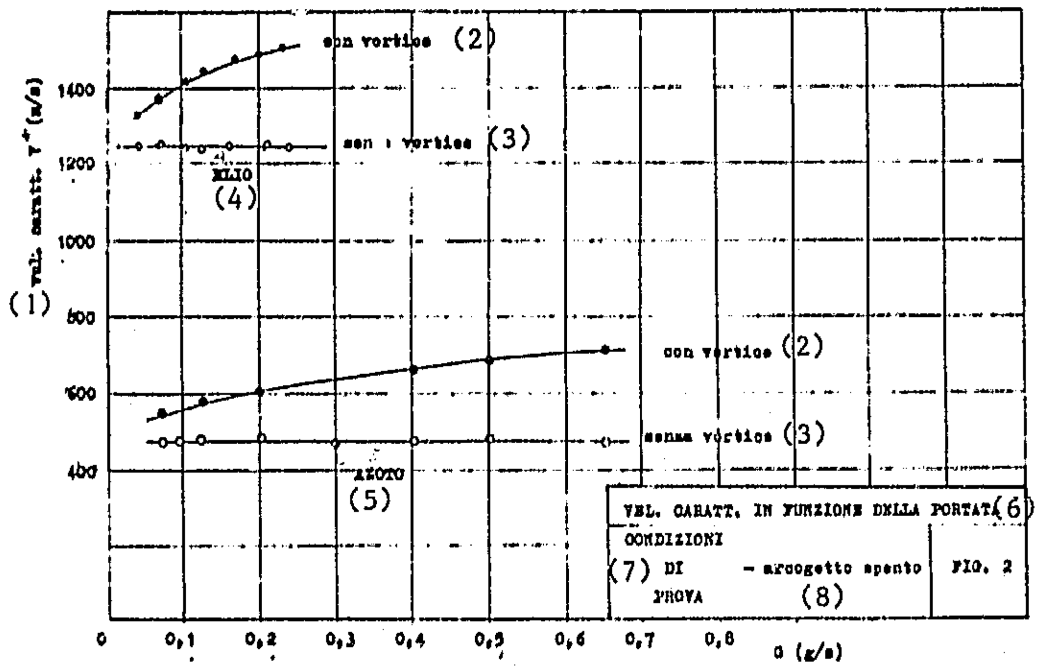


Figure 1 General schematic of the test facility
(Please see key on following page)

KEY to Figure 1, page 13): 1 Exhaust 2 Vacuum pump 3 Cooled diffuser 4 Vacuum chamber 5 Thrust indicator 6 Porthole 7 Coupling 8 Oil for labyrinth seals 9 RF primer 10 Arc voltage 11 Chamber pressure signal 12 Coil voltage 13 Thrust signal 14 Feed gas 15 Gas flow meter 16 Amplifiers 17 Command and control console 18 Line 19 Arc current signal 20 Arc voltage signal 21 Oscillograph 22 Arc-jet



KEY 1 Characteristic velocity V* 2 with vortex 3 without vortex 4 Helium 5 Nitrogen 6 Characteristic velocity as a function of gas flow 7 Test conditions 8 Arc-jet off

Figure 2

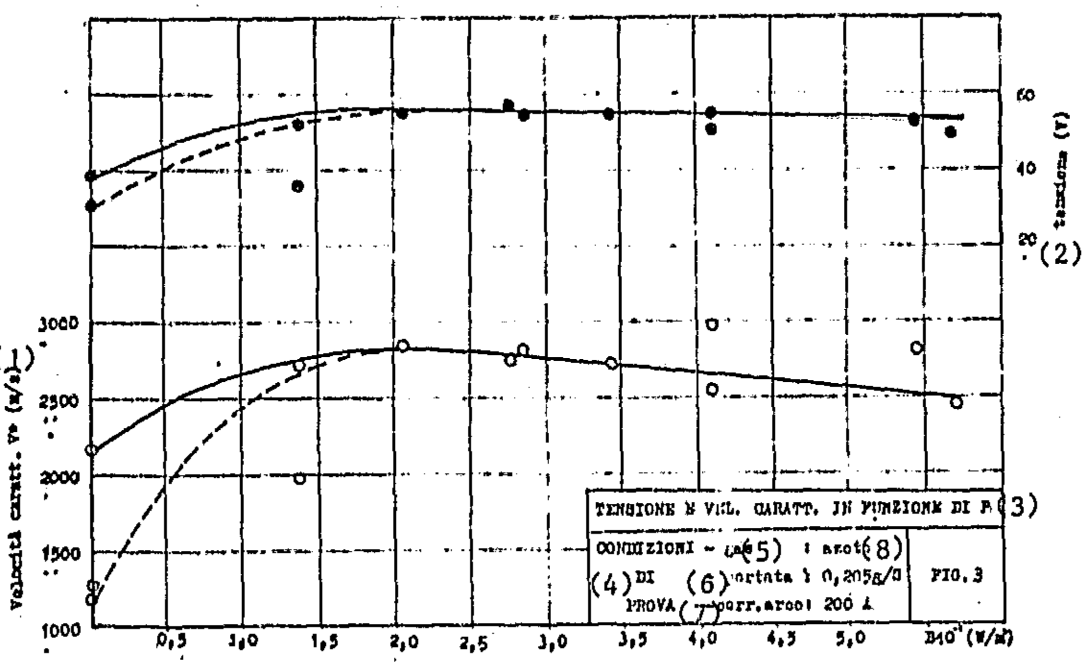


Figure 3

KEY to Figures 3 and 4: 1 Characteristic velocity 2 Tension 3 Tension and characteristic velocity as a function of B 4 Test conditions 5 Gas 6 Flow rate 7 Arc current 8 nitrogen

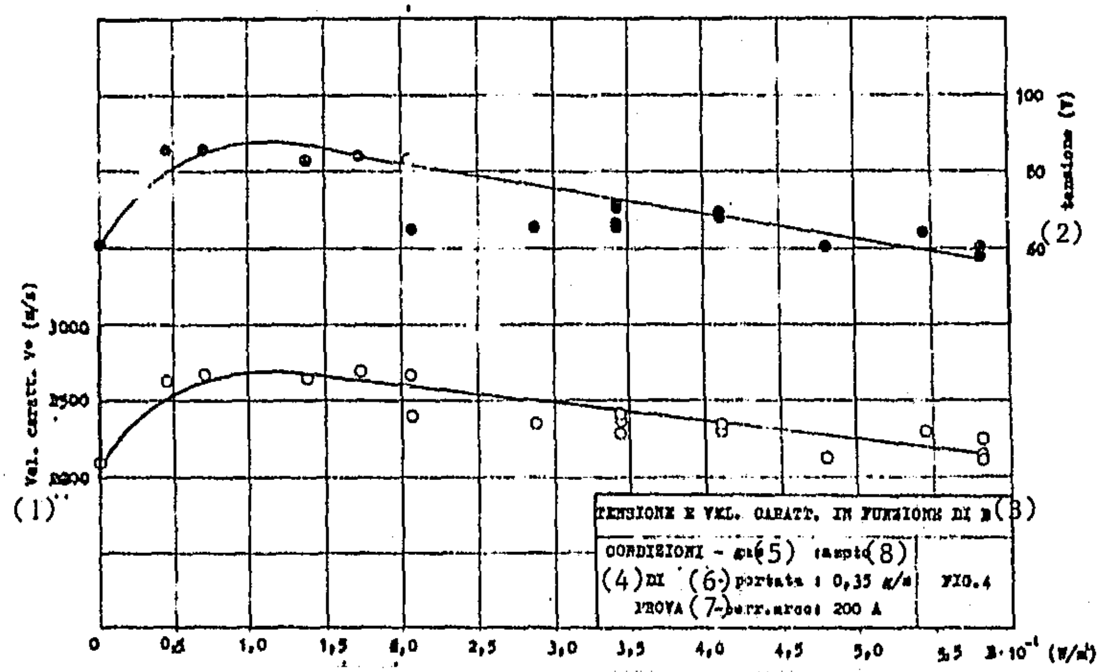


Figure 4

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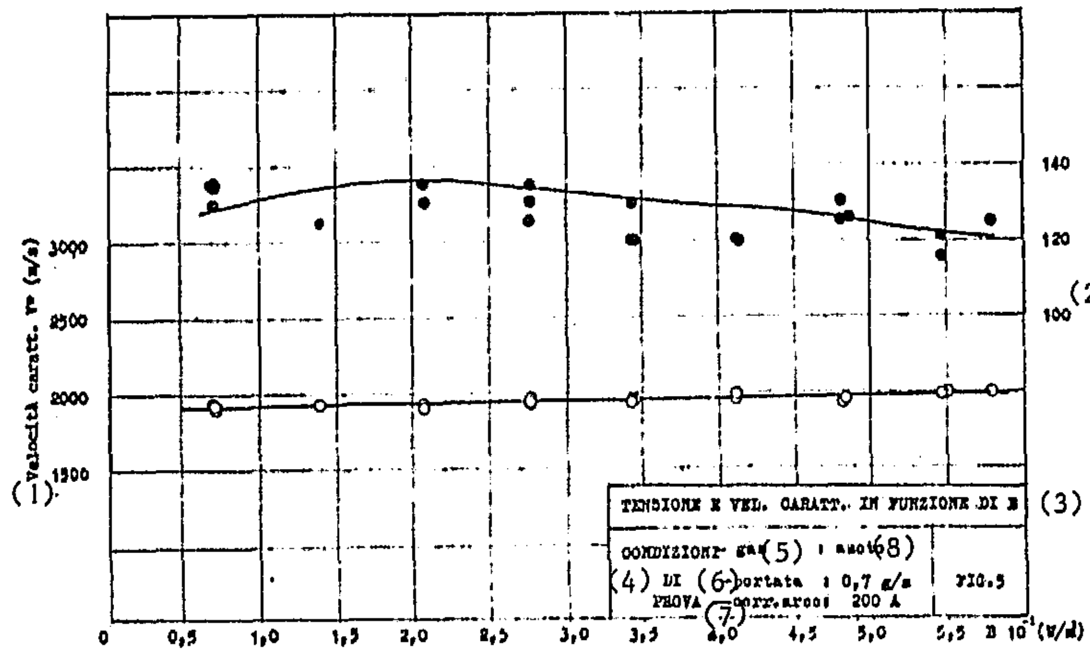

Figure 5

KEY to Figures 5 and 6: 1 Characteristic velocity 2 Tension 3 Tension and characteristic velocity as a function of B 4 Test conditions 5 Gas 6 Flow rate 7 Arc current 8 Nitrogen 9 Helium

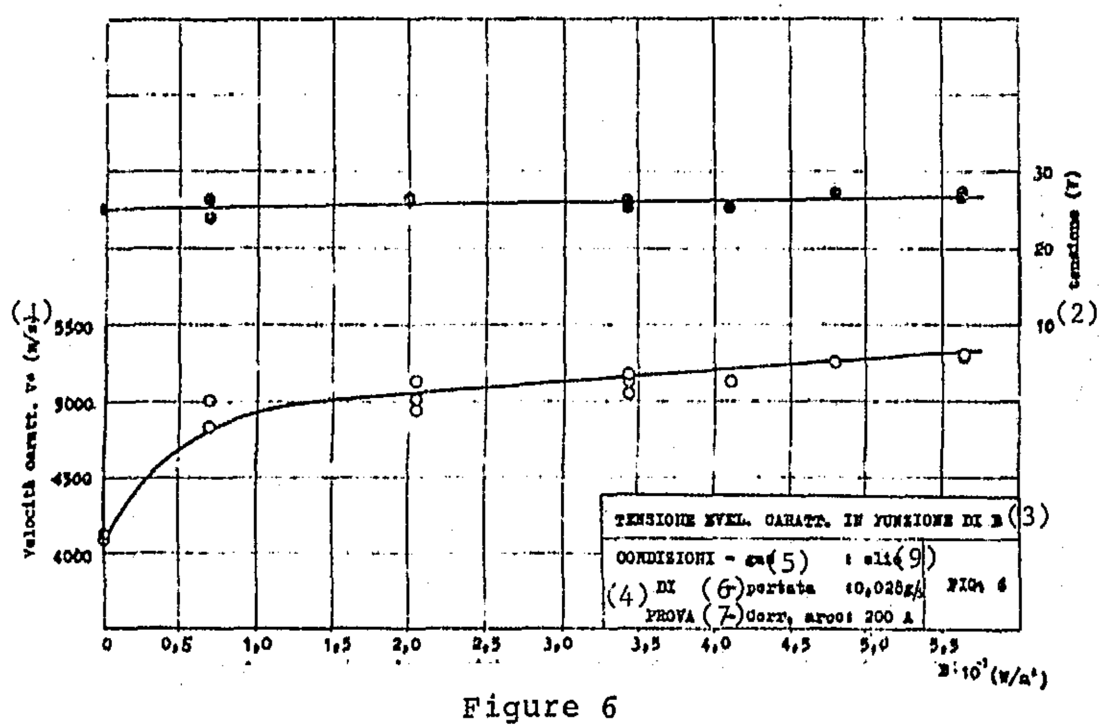

Figure 6

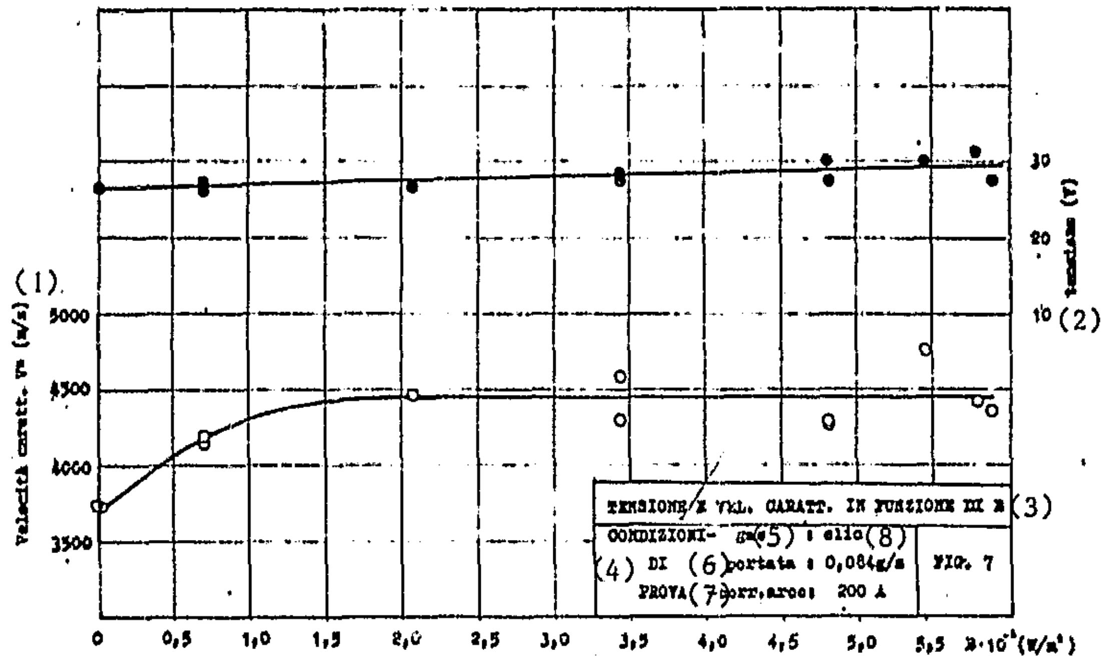

Figure 7

KEY to Figures 7 and 8: 1 Characteristic velocity 2 Tension 3 Tension and characteristic velocity as a function of B 4 Test conditions 5 Gas 6 Flow rate 7 Arc current 8 Helium

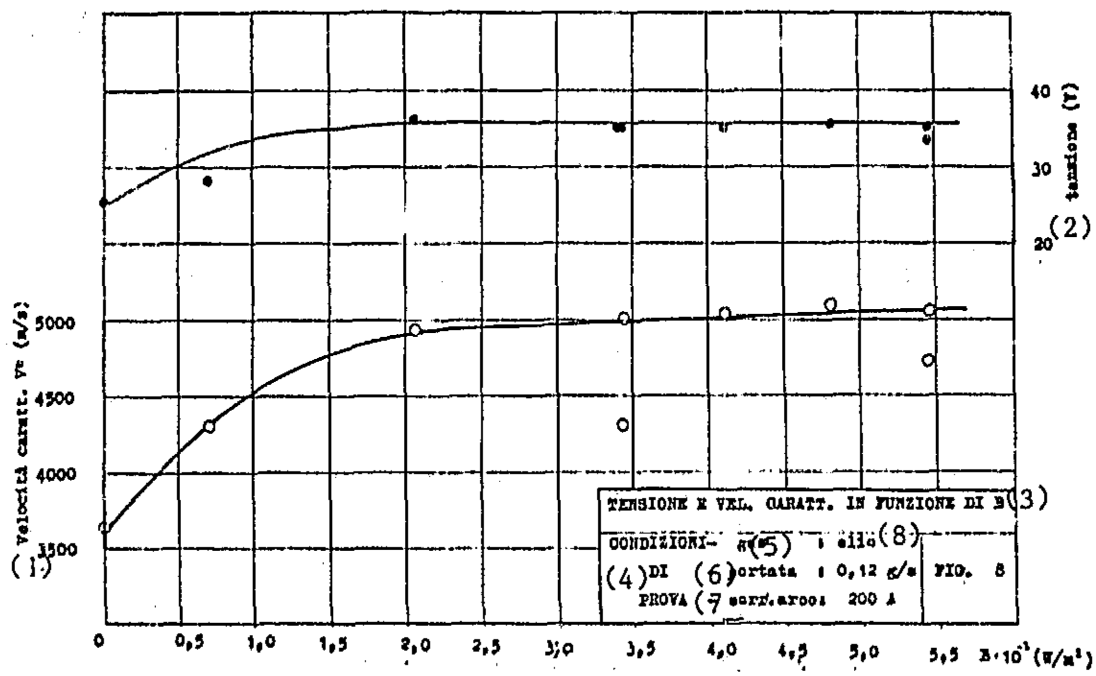

Figure 8

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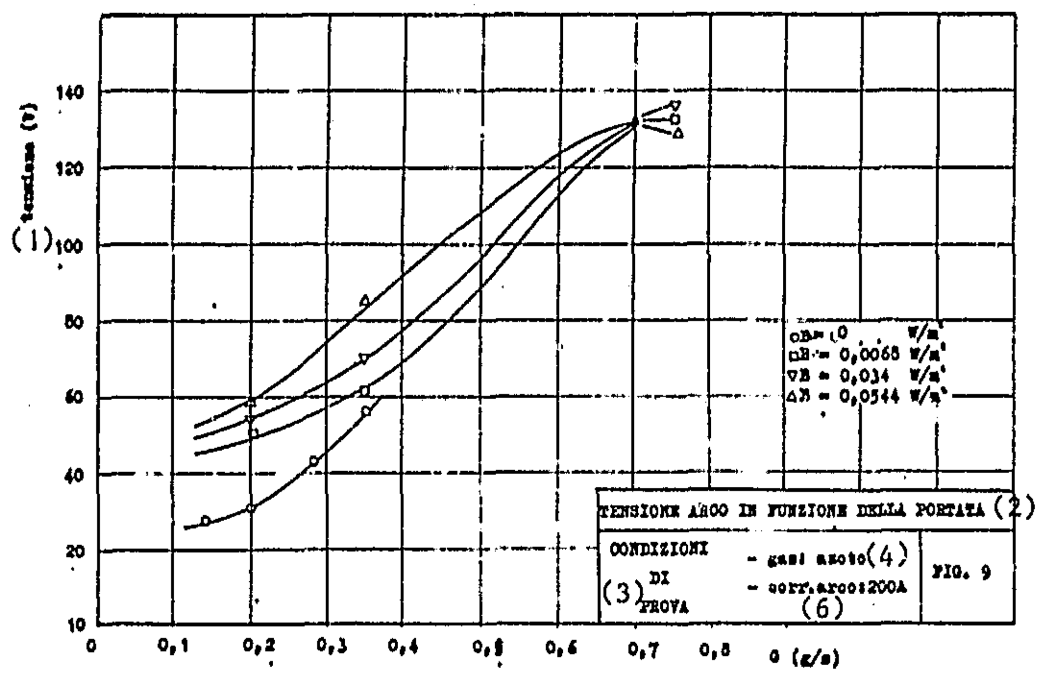

Figure 9

KEY to Figures 9 and 10: 1 Tension 2 Arc tension as a function of flow rate 3 Test conditions 4 Gas: nitrogen 5 Gas: helium 6 Arc current

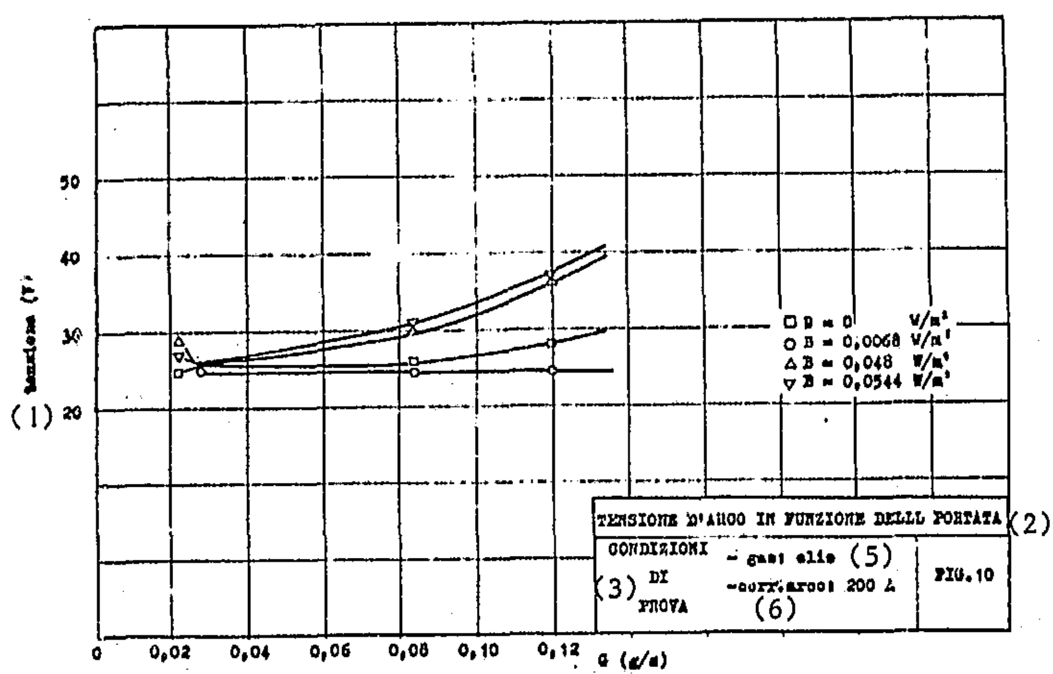

Figure 10

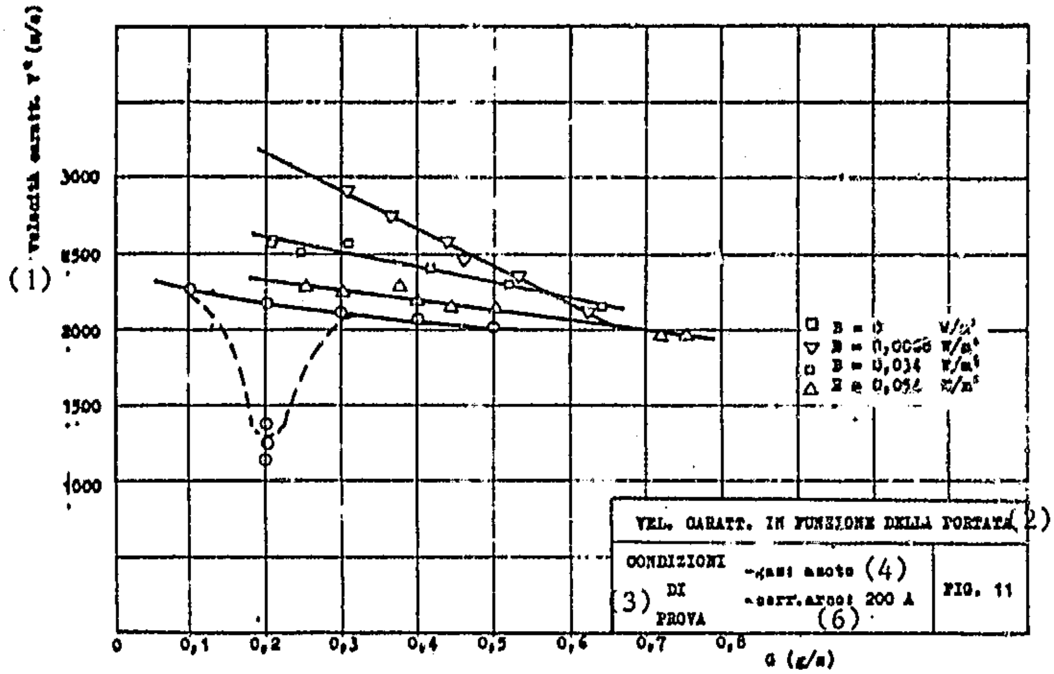

Figure 11

KEY to Figures 11 and 12: 1 Characteristic velocity 2 Characteristic velocity as a function of flow rate 3 Test conditions 4 Gas: nitrogen 5 Gas: helium 6 Arc current

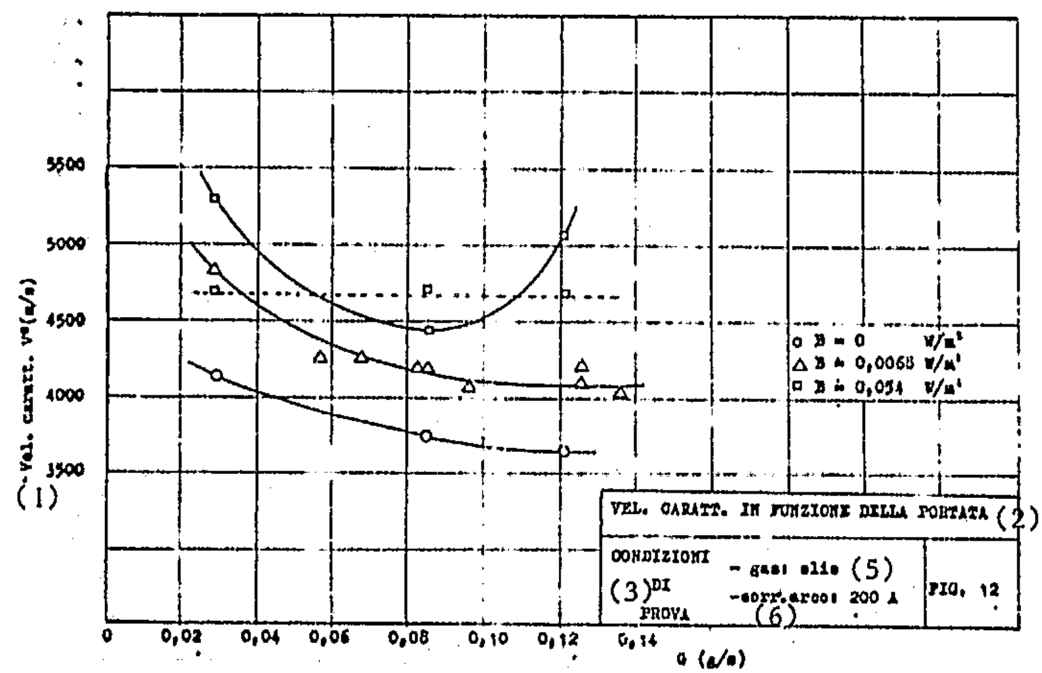

Figure 12