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THE ATMOSPHERIC REENTRY SIMULATOR IN NAPLES

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Abstract

The High-Enthalpy Blow-Down Arc Facility (HEBDAF) at the Department of Space Sciences and Engineering (DISIS) in Naples has been already used for experimental and theoretical studies in the plasma diagnostic field. The facility has been recently adapted for the simulation of the hypersonic conditions found by space vehicles in the reentry phase.

In the first part of the present paper the HEBDAF main technical characteristics and the improvements made to satisfy the new simulation requirements, are described.

In the second part the experimental techniques and numerical models used to evaluate the thermofluidynamic free-stream parameters are described. A numerical model, to compute the thermal response of an ablative material during an arc-jet test, is also described.

In the third part the results of calibration tests are presented. In these tests total and local enthalpy, pressures and heat fluxes are measured at different electrical power and gas flow rates. These data, together with other parameters, numerically computed, allow to evaluate a preliminary operating envelope for the HEBDAF and to establish its performances. Also the results of some ablation tests, performed on a silicon-based ablative material, already qualified for reentry applications are shown.

Introduction

Renewed interest in hypersonic aerodynamics, driven by the projects of trans-atmospheric vehicles (e.g. aerospace planes), involves a large amount of basic and applied research in this field. Small, low cost, flexible facilities are very amenable to achieve this goal. Such is the case of the High Enthalpy Blow-Down Arc Facility at the Department of Space Science and Engineering "L.G. Napolitano" in Naples. This small plant, already employed for experimental and theoretical studies in the plasma diagnostic field(1), has been recently adapted to be used as an atmospheric reentry simulator, with particular emphasis on the reproduction of the heat fluxes occurring during reentry(2).

For this purpose the facility has been equipped with:

1) transducers to measure the stagnation pressure of the jet, the static pressure at the nozzle inlet and outlet, and in the test chamber,
2) a calorimeter for the heat flux measurement,
3) a diagnostic system, based on a water-cooled probe, to measure local total enthalpy and oxygen concentration in the arc-jet.
4) a control and data acquisition system to manage from a Personal Computer both the arc-jet starting procedure and data acquisition.

Since in a high-enthalpy supersonic flow it is very difficult to directly measure all the thermofluidynamic parameters of interest, an experimental-numerical methodology has been implemented. This methodology allows the evaluation of all free-stream properties (velocity, density, temperature, chemical composition) from the experimental data(3).

HEBDAF calibration tests included measurements of average total enthalpy, local enthalpy, oxygen concentration, pressures and heat fluxes. Extensive heat flux measurements were performed on bluff cylindrical calorimeters. The results are compared with the ones obtained by formulas(4) that include the effects of the surface catalicity.

To assess the HEBDAF performances, a number of ablation tests was started. A silicon based polymeric material, already qualified for reentry applications, was used. The thermal response of the material to the heat flux, measured by thermocouples inserted in the specimen, was also computed by an ablation process mathematical model, based on the equation energy.

Experimental Apparatus

Facility

A functional scheme of the HEBDAF is shown in fig.1.

The HEBDAF consists of:

1) DC electric arc-heater, 80 [kW] maximum power, operating with pure nitrogen,
2) a device to mix hot nitrogen with cold oxygen (mixing chamber), to simulate air composition. The oxygen injection is made through two holes, 1 [mm] diameter, in such a way that the cold gas, flowing along the mixing device wall, prevents overheating,
3) a supersonic conical nozzle (area ratio 4).
4) a cylindrical vacuum test chamber, equipped with glass windows, in which the high enthalpy flow

exhausts as a free jet. Typical pressure level in the test chamber is 200 [Pa].

5) two cooling systems. One, operating with distilled water, cools the arc-heater, the nozzle and the gas heat-exchanger. The another one, operating with drink water, cools the test chamber, the vacuum pumps and the distilled water of the first cooling system.

6) a panel, equipped with control and measurement instruments, for the manual control of the facility.

Reference 5 provides more detailed information about the HEBDAF.

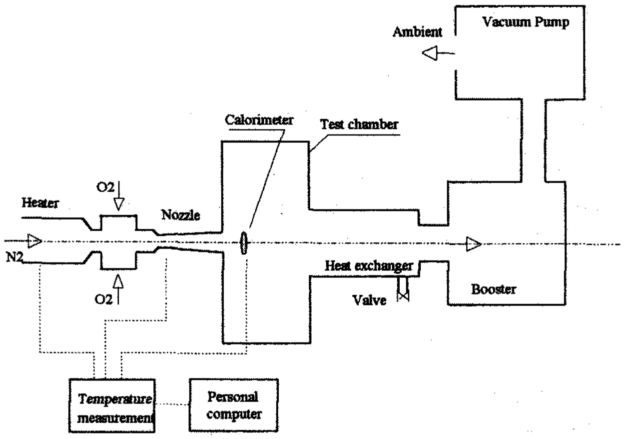

Fig. 1 HEBDAF set up

Instrumentation

The gas mass flow rates (nitrogen and oxygen) are measured by two Brooks thermal mass flow-meters (mod.5853S and 5851S). Coolant flow rates are measured by Fisher & Porter variable-area flow-meters. Electrical parameters (i.e. voltage and current) supplied to the arc-heater are measured by analog instruments.

A dedicated electronic system allows to measure and store the temperatures from eight thermocouples located on: the arc-heater, the nozzle and other water cooled components.

Pressure measurements are made by transducers. All of them have been calibrated by a MacLeod vacuum gauge.

The heat flux measurement is performed by a mass calorimeter (fig.2). The calorimeter, 15 [mm] outer diameter, 8 [mm] thick, is made of oxygen-free copper and is supported in a shroud by a thermal insulator of low thermal conductivity. The calorimeter temperature is measured, as function of time, by a chromel-alumel thermocouple.

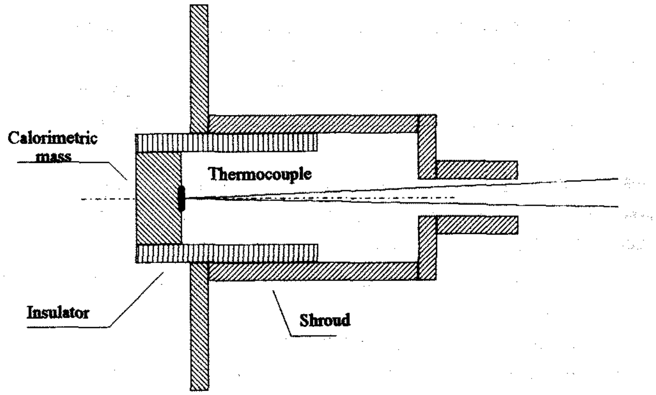

Fig. 2 Cross section of the calorimeter

The probe-based system (4 [mm] diameter) making local measurements in the "free stream" is shown in fig. 3.

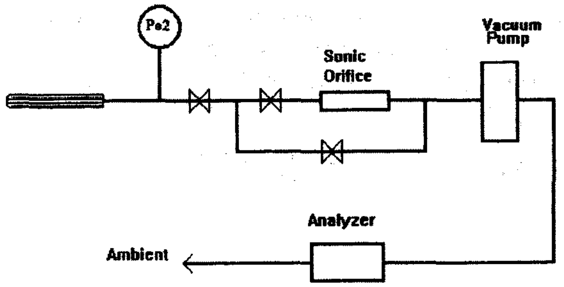

Fig. 3 Probe-based diagnostic system

The central part of the probe supplies a steady flow of sample gas to a sonic orifice for the measurement of the mass flow rate. To take a gas sample, an oil-free, high vacuum pump (ultimate pressure 2 [mbar]) is used. Analysis of oxygen concentration in the gas sample is made by a zirconium-oxyde, solid-state analyzer.

Control and data acquisition system

An electronic system (OPTO22) is used to manage both the arc-jet starting procedure and the acquisition of the signals from the HEBDAF. The modularity is an important feature of this system. In fact it results in a high system flexibility, expandability and very simple troubleshooting. The system consists of:

1) a Control Unit, based on a Local Controller (LC2) equipped with a Z80AD microprocessor. The Local Controller is able to carry out serial communications with the host computer (IBM DX2 486/66) and the Digital/Analog stations.

2) Digital Input/Output unit, containing two stations each equipped with a brain board (that carries out serial communications with the LC2 and also performs control functions at each channel of I/O), and 14 digital I/O modules;
3) Analog Input Unit, containing one station equipped with the brain board (having the same functions as the Digital I/O Unit) and 21 analog I/O modules.

Main functions of the Control and Data Acquisition System are :
1) management of the arc-jet starting procedure
2) control and acquisition of all operating parameters (arc voltage and current, temperatures, pressures, mass flow rates);
3) real time monitoring of the test, and storage of acquired data;
4) elaboration of the test data.

Measurement Techniques

Enthalpy measurements

The primary method to evaluate the flow total enthalpy is the energy balance method(5,6). The average enthalpy of the gas is evaluated by subtracting from the input electric power the losses due to the cooling water:

$$\overline{H}_g = \frac{VI - (\dot{m}c\Delta T)_h - (\dot{m}c\Delta T)_n}{\dot{m}_g} \qquad (1)$$

V and I are the arc voltage and current, $(\dot{m}c\Delta T)_h$ and $(\dot{m}c\Delta T)_n$ are the power losses for the arc-heater and the nozzle, $\dot{m}_g$ is the gas mass flow rate.

The relative uncertainty on the measured enthalpy was estimated to range from 5% to 10%, depending on power levels to the arc.

The water-cooled probe shown in fig.3 is used to measure the flow local enthalpy by a "tare" measurement technique(7). During the "tare" measurement, a valve in the gas sample line is closed to prevent gas from entering the probe. At the same time, the coolant temperature rise and flow rate are measured. The valve is then open, allowing the gas sample to flow through the probe. The same measurements are performed at the probe exit. The measurements of the steady gas sample temperature and flow rate are also performed. The rate of heat removal from the gas sample is thus given by the difference between the two coolant rates:

$$H_g = \frac{\dot{m}_s c_{pg} T_g + (\dot{m}c\Delta T)_f - (\dot{m}c\Delta T)_t}{\dot{m}_s} \qquad (2)$$

where: $\dot{m}_s$ is the sample gas mass flow rate, $\dot{m}_s c_{pg} T_g$ is the gas enthalpy at the probe exit, $(\dot{m}c\Delta T)_f$ and $(\dot{m}c\Delta T)_t$ are the power losses during "flow" and "tare" measurements.

This technique was found to be quite successful. In fact the "tare" measurement eliminates both the error due to heat transfer from the outer part of the probe and the error due to probe radiation heating.

Pressure measurements

During each test the following pressures are measured:
1) the pressure at the entrance of the mixing chamber,
2) the static pressure at the nozzle exit,
3) the static pressure in the test chamber.

The stagnation pressure, behind a normal shock, is also measured by the calorimetric probe during the "tare" phase.

Heat flux measurements

To evaluate heat fluxes, the mass calorimeter is located along the jet axis (see fig.1). The working principle of this gauge relies on storing the heat flux, incident upon its surface, in a short time interval. Transient heat flux is determined by measuring the slope of the calorimeter temperature time profile, and by knowing physical and thermal properties of the calorimetric mass(8):

$$\dot{q}(t) = \rho c l \left(\frac{\partial T}{\partial t} \right)_t \qquad (3)$$

ρ is the density of the gauge material (copper), l is the thickness of the calorimetric mass, dT/dt is the slope of the time temperature distribution.

Mathematical models and numerical computations

Arc jet model

A mathematical model, describing the non-equilibrium aerothermochemical evolution of the flow in the HEBDAF, has been specifically developed(3). This model computes the gas composition, the fluid-dynamic parameters and the transport coefficients necessary to evaluate all the characteristic numbers (Mach, Reynolds, Lewis, and so on) defining the test condition.

The related numerical code requires in input the parameters measured during the test: voltage, current, oxigen and nitrogen mass flow rates, cooling water flow rates.

The code follows the gas evolution across the arc-heater, the mixing-chamber and the nozzle. The flow

parameters at the exit of the nozzle are considered to be the "free stream" ones in the test section.
The arc-heater is schematized in two parts: a conical duct (15 [mm] inlet diameter, 8 [mm] outlet diameter, 9 [mm] length) and a circular duct (8 [mm] diameter, 23 [mm] length). The electrical discharge is supposed to take place only in the cylindrical part of the arc-heater. The mixing-chamber is a cylindrical duct (8 [mm] diameter, 22 [mm] length). Here the energized gas, coming from the arc-heater ("hot" N_2), can be mixed with a gas at ambient temperature ("cold" O_2). The nozzle is a convergent-divergent conical duct. The inlet and the outlet diameters of the nozzle are 22 [mm], the throat diameter is 11 [mm]. The length of the convergent (i.e. subsonic) part is 16 [mm]. The length of divergent (i.e. supersonic) part is 61 [mm].
The numerical model is referred to a mixture of nitrogen and oxygen that dissociate and vibrate. The gas mixture is made of five chemical species: atomic and molecular oxygen, atomic and molecular nitrogen and nitrogen oxide. The chemical kinetics relies on six dissociation/recombination equations:

$$N_2 + M \rightleftarrows 2N + M$$
$$O_2 + M \rightleftarrows 2O + M$$
$$NO + M \rightleftarrows N + O + M$$
$$N_2 + O_2 \rightleftarrows 2NO$$
$$O_2 + N \rightleftarrows NO + O$$
$$N_2 + O \rightleftarrows NO + N$$

The mathematical model consists of: 3 balance equations (mass, momentum and energy), 2 thermodynamics state equations for thermally perfect gases, 2 species conservation equations, 3 dissociation/recombination equations, 3 equations for the vibration. The system, written in terms of differential equations, is integrated by a fourth order Runge Kutta algorithm. The transport coefficients, i.e. viscosity, thermal conductivity and mass diffusivity are computed by the kinetic theory of gases (9,10).

Heat flux computation

Measured heat fluxes are compared with the ones obtained by using the Fay-Riddel formula for fully catalytic walls(9):

$$\dot{q} = 0.76\,\mathrm{Pr}^{-0.6}(\rho_e\mu_e)^{0.4}(\rho_w\mu_w)^{0.1}\sqrt{\left(\frac{du_e}{dx}\right)_s}\,(h_{0e} - h_w)$$

$$\left[1 + \left(\mathrm{Le}^{0.63} - 1\right)\left(\frac{h_D}{h_{0e}}\right)\right] \qquad (4)$$

$$h_D = \sum_i \alpha_{ie}(\Delta h_f)^0_i, \quad \left(\frac{du_e}{dx}\right)_s = \frac{1}{R}\sqrt{\frac{2(p_e - p_\infty)}{\rho_e}}$$

h_0 is the total enthalpy, α_i and $(\Delta h_f)^0_i$ are the mass fraction and the zero-point heat of formation of the i^{th} specie, R is the body nose radius of curvature, subscripts "e", "w", "∞" and "s" are for boundary layer edge, wall, free stream and stagnation point.

Polymer composite materials ablation model

To analyze the thermal response of a polymer composite material, undergoing decomposition, a one-dimensional transient heat conduction equation was used. An additional term (Q_i), accounting for the energy associated with the material thermal decomposition(11), was considered:

$$\rho c_p \frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial x^2} - \frac{\partial \rho}{\partial t}\left(Q_i + c_p T\right) \qquad (5)$$

where x is a non-dimensional abscissa, starting from the face of the material exposed to the heat flux.
The term on the left side of the eq.(5) represents the rate of change of internal energy of the material. The first term on the right side represents the conduction flux, and the second term represents the rate of heat production/destruction due to the material decomposition. The boundary and initial conditions are :

$$-k\frac{\partial T}{\partial t} = \dot{q}_{conv} + \dot{q}_{rad} \qquad (6)$$

at x=0 and t>0;

$$\frac{\partial T}{\partial x} = 0, \quad \dot{m}_g = 0 \qquad (7)$$

at x=l and t>0.
The thermal conductivity and the thermal specific heat are bulk values, weighted by the fractional extent of decomposition:

$$k = Fk_v + (1 - F)k_c \qquad (8)$$

$$c_p = F c_{pv} + (1 - F) c_{pc} \qquad (9)$$

subscripts "c" and "v" are for "char" and "virgin", respectively, $F = (m - m_f)/(m_i - m_f)$ is the fraction of the virgin material remaining in the solid matrix. Eq.(5) is solved using an explicit finite difference scheme. The time derivatives were represented by forward finite differences, the space derivative by central finite differences.

Results

Total enthalpy profiles along the nozzle exit radius, as measured by the calorimetric probe, are shown in fig.4 for a pure nitrogen flow and for a simulated air flow (80% nitrogen - 20% oxygen). The total enthalpy values, obtained by integrating these profiles, agrees with the ones obtained by the energy balance, considering the experimental uncertainty of the measurements.

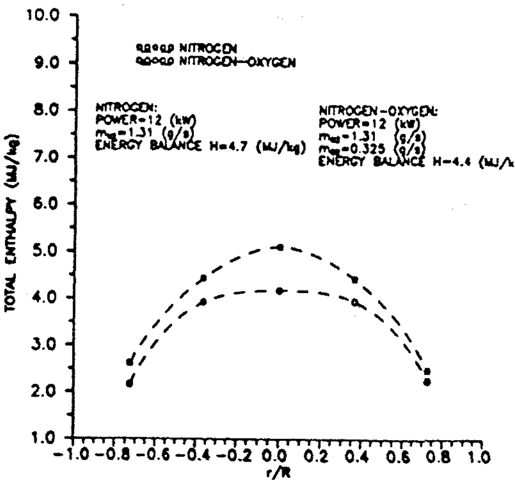

Fig.4 Total Enthalpy profiles

The heat fluxes, measured by the calorimeter, for simulated air, are shown in fig.5.

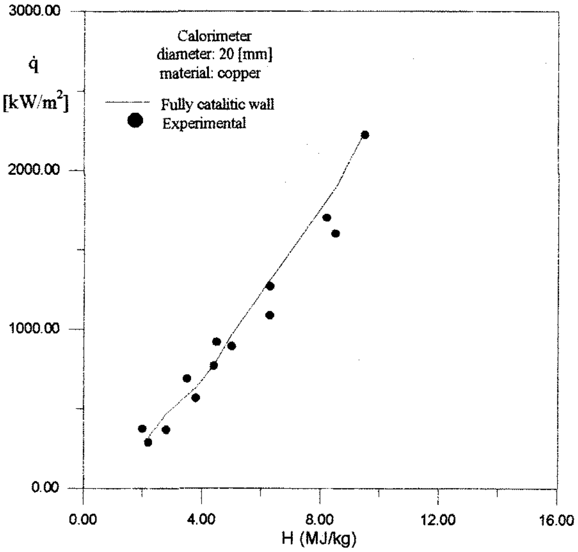

Fig. 5 HEBDAF heat flux measurements vs. numerical computations

To estimate the simulation capabilities of the HEBDAF, the measured stagnation pressures (p_0) versus the flow total enthalpy (H) are compared in fig.6 with the space capsule CARINA reentry path.

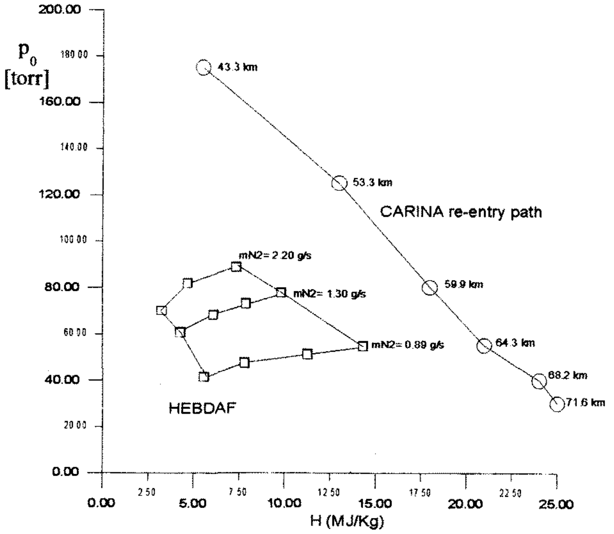

Fig.6 HEBDAF simulation capabilities vs. CARINA reentry path

Another comparison to assess the performances of the HEBDAF was made with the plasma wind tunnel SCIROCCO, to be built in Capua by the Italian Aerospace Research Center (CIRA). The stagnation point heat flux ($\dot{q}_0$) vs. the stagnation point pressure (p_0) is shown in fig.7.

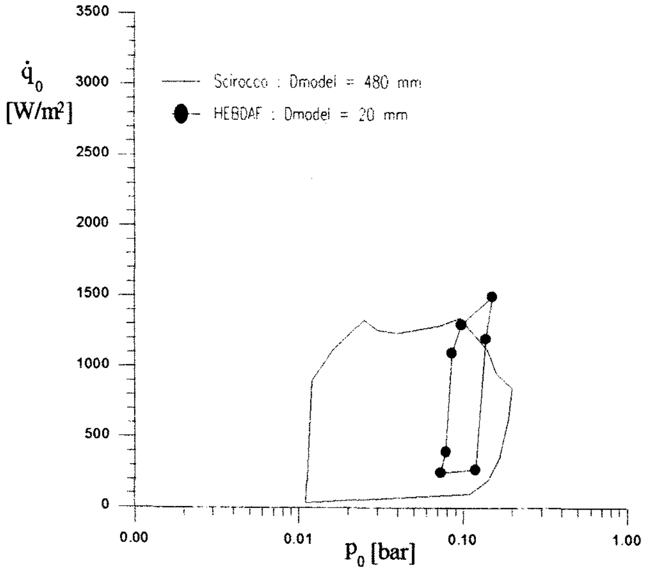

Fig. 7 SCIROCCO-HEBDAF comparison

Fig.7 shows that the HEBDAF capabilities, in generating heat fluxes, are comparable with the ones achievable by a more and more expensive arc-tunnel. Numerical results were obtained by processing the experimental tests obtained at these test conditions:

$\dot{m}_{N_2}$ = 1.31 [g/s],

$\dot{m}_{O_2}$ = 0.32 [g/s],

electric power (P) : from 12 to 29 [kW].

Typical fluidynamic parameters (related to the above test conditions) along the nozzle are shown in fig.8.

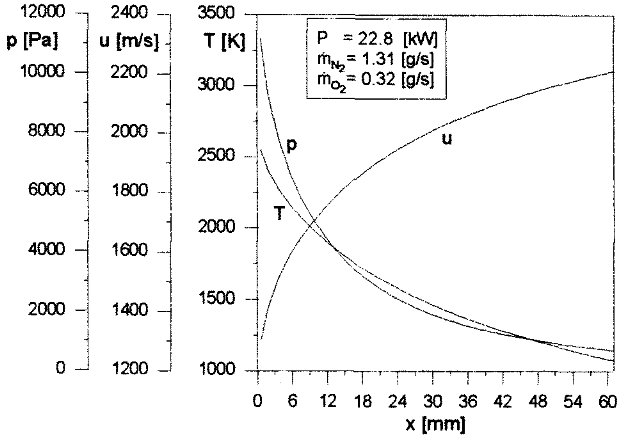

Fig. 8 HEBDAF flow properties along the nozzle

In fig.9 the mass fractions (α) of the five chemical species as a function of the electric power are shown.

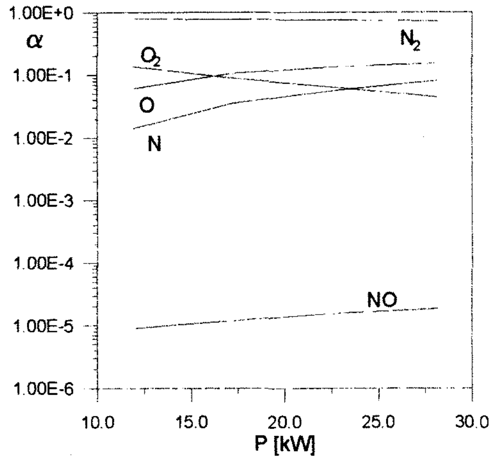

Fig.9 Mass fractions ($\dot{m}_{N_2}$=1.31, $\dot{m}_{O_2}$=0.32 [g/s])

In fig.10 the "free stream" characteristic simulation parameters, i.e. the Reynolds number (Re), the viscous interaction parameter $\left(M^3/\sqrt{Re}\right)$ are shown.

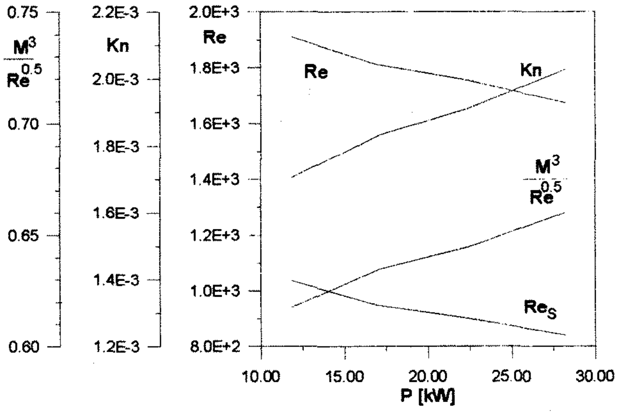

Fig.10 Characteristic numbers profiles vs arc electrical power ($\dot{m}_{N_2}$=1.31, $\dot{m}_{O_2}$=0.32 [g/s])

The Mach number (not shown in figure) ranges between 3.05 and 3.12. In the same figure the rarefaction parameters, i.e. the Knudsen number (Kn) and the Reynolds number behind a normal shock (Re_S) are also shown. Both the Reynolds numbers (Re, Re_S) and the Knudsen number are related to the nozzle exit diameter (22 [mm]). The flow regime can be considered continuum low density (slip flow) for a model characteristic dimension of $O(10^{-2})$ [m], like the nozzle exit diameter. In fact according to the flow rarefaction criterion(12) the slip flow regime, is defined by $10<Re_S<10^4$ for a sphere, and by $10^{-2}<Kn<1$ for a cylinder and a flat plate.

The diffusion charateristic numbers, i.e. the Prandtl number (Pr), the Lewis number (Le), the Schmidt number (Sc), are shown in fig. 11 vs. the electrical power to the arc heater.

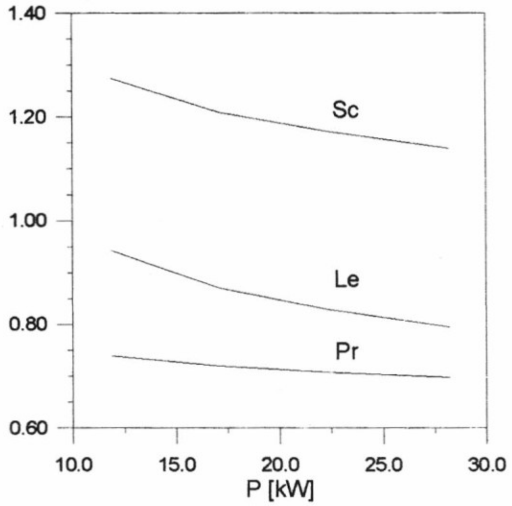

Fig.11 Prandtl, Lewis and Schmidt numbers vs arc electrical power ($\dot{m}_{N_2}$=1.31, $\dot{m}_{O_2}$=0.32 [g/s])

As preliminary utilization of the HEBDAF for reentry applications, ablative tests were made on a polymeric material already qualified for reentry applications. In fig.12 a specimen of the material after exposure to the arc-jet flow is shown. The ablation test conditions were:
average total enthalpy: 4.5 [MJ/Kg]
cold wall heat flux: 732 [kW/m^2]
exposure time of the specimen: 120 [s]

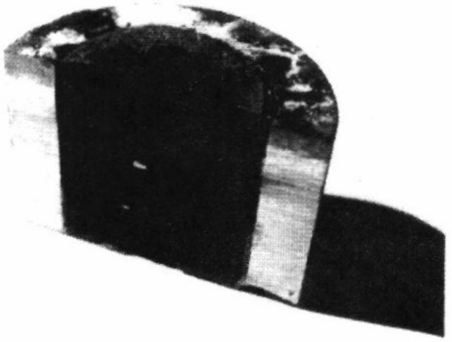

Fig. 12 Specimen of ablative material

The specimen, a cylinder 20 [mm] diameter and 18 [mm] length, was instrumented with three chromel-alumel thermocouples. These were located on the specimen center-line at 4.4, 8.0 and 15.4 [mm], starting from the face exposed to the flow.

In fig.13 the comparison between predicted and experimental temperature profiles, during the test and the cooling phase of the specimen are shown. The mathematical model predicts with good accuracy the thermal response of the material.

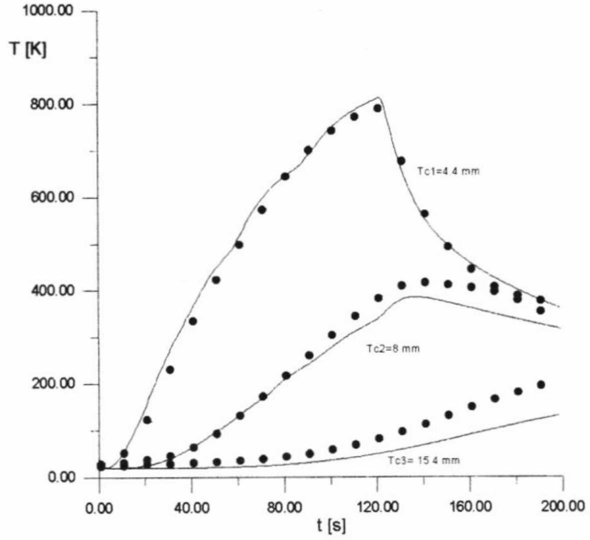

Fig.13 HEBDAF ablation test : experimental vs. numerical results

Conclusions

The High Enthalpy Blow-Down Arc Facility in Naples is an arc-heated facility for the simulation of the aerothermochemical environment experienced by space vehicles during the reentry phase.

In this paper the initial results of an experimental/numerical study to evaluate the thermofluidynamic properties of the high-enthalpy, supersonic flow generated in the HEBDAF are presented.

Future planned developments for this facility are:

1) accurate heat flux measurements on blunt-shaped models, using both mass-type calorimeters and Computerized Infrared Thermography,
2) ablation tests, to evaluate the performances of these materials as Thermal Protection Systems (TPS) for reentry vehicles.

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Centro Italiano Ricerche Aerospaziali (C.I.R.A.) for the electric arc-heater.

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