DESIGN OF SLUG CALORIMETERS FOR RE-ENTRY TESTS

Antonio Esposito(1), Francesco De Rosa(1), Vincenzo Caso(1), Ferruccio Parente(1)

(1)DIAS, University of Naples Federico II, Via Claudio, 21 – 80125 Naples, Italy, Email: antespos@unina.it

ABSTRACT

The paper deals with the design, manufacturing and test of the "slug" calorimeter, both for ground testing as for dynamic and flight testing.

Applications where the magnitude and duration of heating require a thick slug equipped with several thermocouples due to the appreciable internal temperature gradients. Herein is discussed the possibility of using a single thermocouple application on thick slug calorimeters keeping an acceptable engineering approximation.

It has been found that the equation:

$$\dot{q} = \rho \cdot c \cdot l \cdot \frac{dT}{dt} \qquad (1)$$

would yield heat-rate values very close to the input, provided the temperature measurements were made at a distance from the back face of the slug equal to 60 percent of the calorimeter length. This condition held true for a variety of inputs, both constant and varying. The simplicity of this method, requiring a single-point measurement per calorimeter, could substantially reduce the time and costs involved in investigations of high heat fluxes.

1. INTRODUCTION

The slug calorimeter [1,2], particularly effective in high heat flux measurements arising in re-entry conditions, offers great advantages compared with other solutions in terms of cost and durability.

In the Department of Aerospace Engineering (DIAS) of the University of Naples "Federico II" there is a long experience about measurements of the heat fluxes that occur in high enthalpy supersonic flows during the re-entry from space. Such expertise has been achieved mostly in ground tests performed in the small electric-arc wind tunnel named SPES (Small Planetary Entry Simulator) [3].

The main characteristics of the slug sensor are:

- easy manufacturing and assembly
- no necessity of cooling system
- relatively cheap compared to other types of sensor
- easy installation on monitored parts

Slug calorimeters are extensively used for measurements of constant heat rates, as is a routine in ground tests. The recent project "Cibapark" [4] shared between the Department of Aerospace Engineering of University of Naples (DIAS) and the Italian Center of Aerospace Research (CIRA) allowed to built and test a probe for measurement of high heat fluxes, based on the slug-type sensor. The tests performed in the SCIROCCO Plasma Wind Tunnel at CIRA, confirm that the slug sensor has capabilities which compare to the much more complex Gardon gauge ones available to CIRA, and therefore it represents a technical and economical good alternative to it.

The further step in such research plan has been to use the slug sensor to measure varying heat fluxes, as it happens during the re-entry phase of a space probe.

2. THEORY OF THE SLUG SENSOR FOR CONSTANT HEAT FLUX

The slug-type heat-flux sensor, see Figs.1-2, consists of a small cylinder of metallic material (slug), inserted into the face of the model but isolated from it, whereby it measure the heat flux.

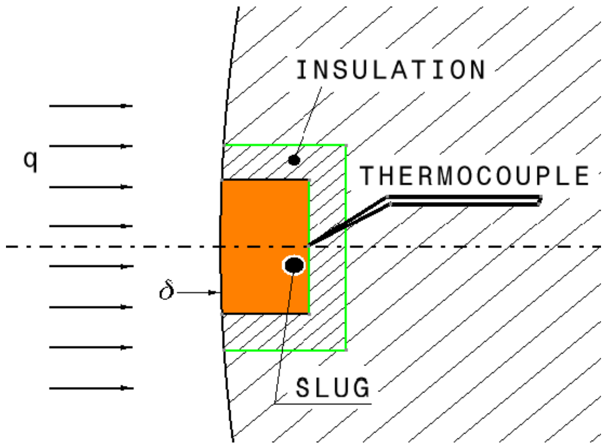

Fig. 1. Single thermocouple Slug-type heat-flux sensor.

The presence of an insulator is required to minimize the heat losses to and from the model, in order to approximate the heat transfer as one-dimensional.

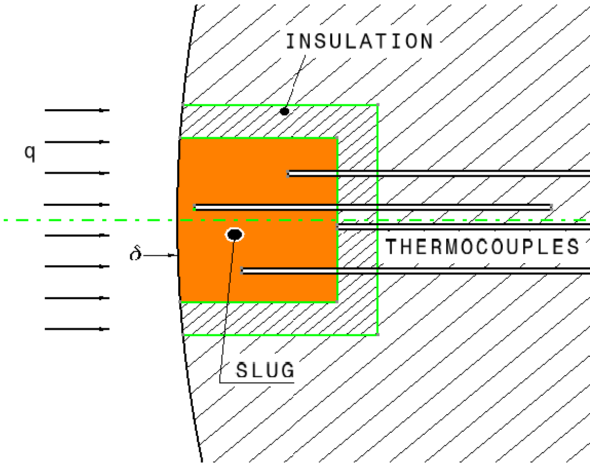

Fig. 2. Multi-thermocouple Slug-type heat-flux sensor.

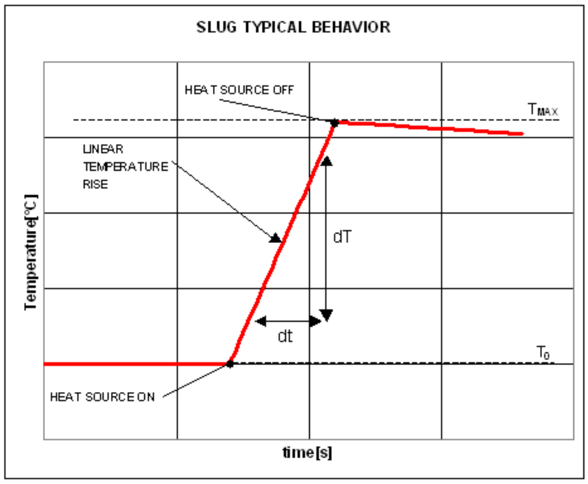

Fig. 3. Measurement with the slug sensor.

In case of thin slugs with non-significant temperature gradients a single thermocouple located on the rear surface of the slug, see Fig. 1, is sufficient to measure the temperature whilst in case of thick slugs with significant temperature gradients several thermocouples located in different positions, see Fig. 2, are needed to monitor the temperature itself.
The heat flux is obtained by means of an energy balance:

$$\dot{q} = \frac{M \cdot c}{A} \cdot \frac{dT}{dt} \tag{2}$$

The measurement of a constant heat flux is performed as shown in Fig. 3. Starting from a reference temperature (room temperature), the sensor is inserted into the stream, and after a short initial transient the temperature increases linearly versus time. Temperature is tracked for a time sufficiently long to enable accurate determination of the derivative *dT/dt*, but that does not compromise the physical integrity of the sensor. At this point the sensor is removed from the flow continuing to acquire temperature data.
The choice of the material used to build the slug involves several considerations. The melting temperature of the front surface is a limiting design parameter. When the surface of the calorimeter is suddenly exposed to a high heat flow, this is initially transmitted by conduction.
The melting does not occur until the surface reaches a critical temperature, which depends on the structure of the material. When the melting begins, the flow by conduction is reduced and a large portion of energy is stored into the phase changing degree of freedom. In this situation the relationship between the heat flux and the temperature of the back surface becomes very complex.

It is therefore necessary to prevent the melting in order to preserve the integrity of the sensor and to maintain a simple relationship between the heat flux and temperature of the rear surface of the slug. The classical solution of the heat conduction on a semi-infinite solid exposed to a sudden constant heat flux can be used to determine the properties necessary to avoid melting. This solution indicates that the time required to achieve the melting, Δt_{mp}, is obtained in the following formula:

$$\Delta t_{mp} = \frac{\pi \cdot k \cdot \rho \cdot c \cdot \Delta T_{mp}^2}{4\dot{q}^2} \tag{3}$$

If Δt_{mp} is greater than the time of exposure of the slug in the flow, the melting does not occur. The materials with high values of *k, ρ, c* and Δt_{mp}, are better to avoid the phenomena of fusion because they allow, for the same heat flux, higher exposure time to flow. Copper is typically a good compromise for its low cost (compared to other materials), easy machinability and large availability.

3. USING THE SLUG SENSOR FOR CONSTANT HEAT FLUX

3.1 Assessment of the Slug sensor by comparison with the Schmidt-Boelter sensor

The operational principle of the Schmidt-Boelter gauge, see Fig. 4, is based on axial heat conduction through a thermal mass backed by an heat sink. For a constant heat-flux at the top surface of the gauge, a constant temperature difference is established between the top and the bottom surfaces of the thermal mass. This temperature difference is measured by a multijunction thermopile to provide a high sensitivity sensor. A thermocouple is measuring the back side temperature of the thermal mass to provide the sensor surface temperature during testing. Using conventional materials, the sensor has a maximum continuous service temperature of about 600 [°F]. The material and thickness of the thermal mass determine the time response of the Schmidt-Boelter gauge.

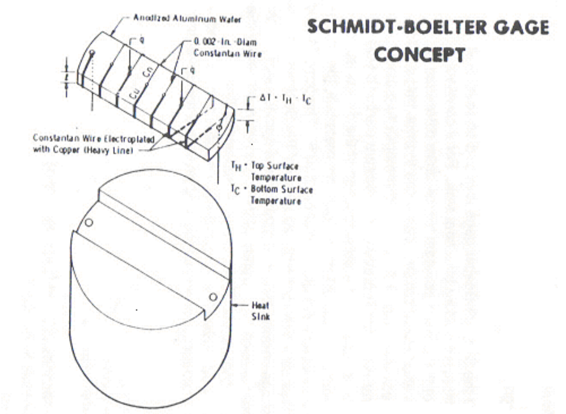

Fig. 4. Schmidt-Boelter type sensor

The Schmidt-Boelter gauge here used is the SBG01-200 model from Hukseflux. Its calibration data are:

- sensitivity: 0.154 [mV m^2 kW^{-1}]
- resistance: 27.1 [Ohm]

The Slug calorimeter was hand-crafted in laboratory. The slug sensor itself is a cylinder of OFHC copper $\phi=5[mm]$, $l=5[mm]$. The insulation is a low-conductivity ceramic. A Chromel-Alumel (K type) thermocouple is soldered at the back face of the Slug. Fig. 5-6 show the sensors mounted on probes and ready for the tests.

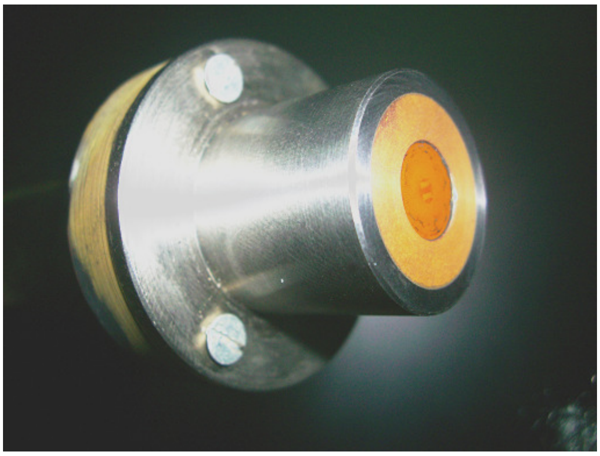

Fig. 5. Schmidt-Boelter Sensor used at DIAS

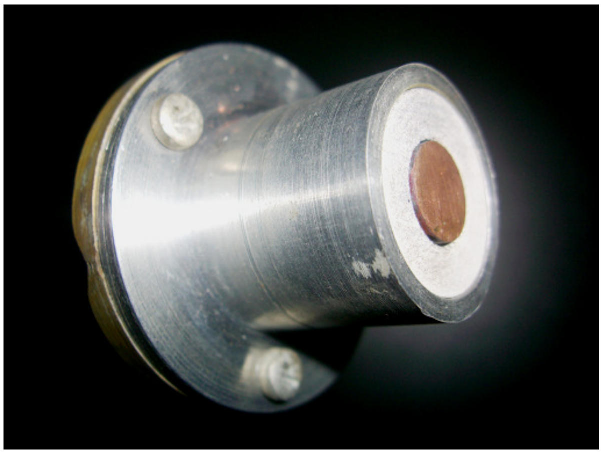

Fig. 6. Slug Sensor used at DIAS

The Schmidt-Boelter and the Slug sensor have been calibrated relatively to a reference sensor, which is traceable to NIST. The calibration is made in a side-by-side comparison using a high-intensity lamp.
For the Schmidt-Boelter sensor the overall uncertainty statement according to ISO is estimated to be within ±3 %, based on a standard uncertainty multiplied by a coverage factor k=2, providing a level of confidence of 95%. In our application other errors have been added to this error, due to data acquisition system.
The total uncertainty is estimated to be within ±5%. For the Slug sensor an uncertainty analysis was made following the procedure proposed by Coleman and Steel [5]. By this procedure the Slug total uncertainty is estimated to be within ±10%.

- **Preliminary Tests**

Preliminary tests were performed by means of an electric hot-air generator. A comparison between the two sensors is shown in Fig. 7-9 using three air speeds.

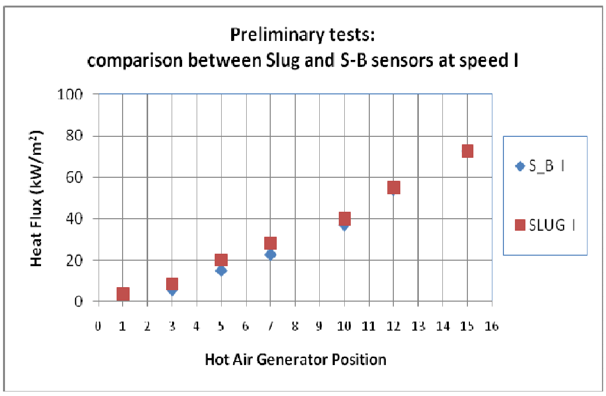

Fig. 7. Slug versus S-B sensors at speed I

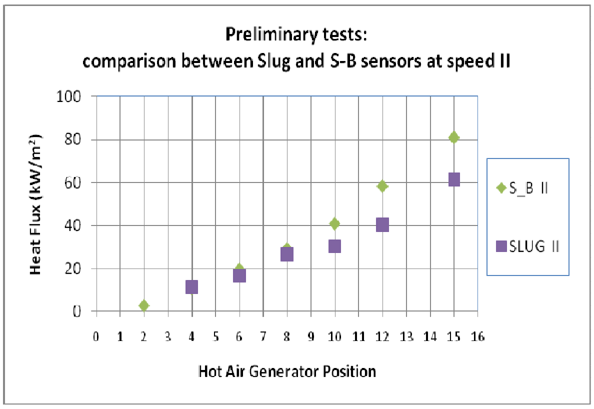

Fig. 8. Slug versus S-B sensors at speed II

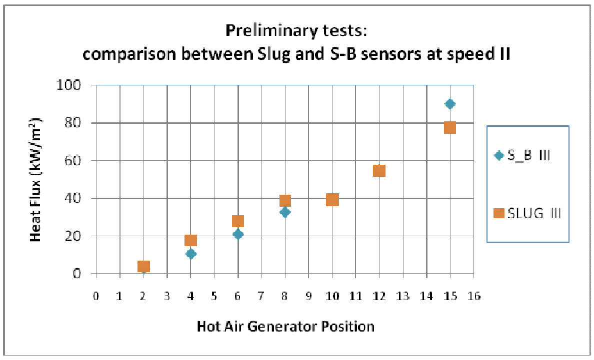

Fig. 9. Slug versus S-B sensors at speed III

The main goal of preliminary test was to check that sensors and data acquisition system were properly working. We have observed a good agreement between the two sensors with a slight difference at the speed II.

- Tests in a pilot plasma wind tunnel

The pilot wind tunnel SPES is shown in Fig. 10-11.

Fig. 10. The Small Planetary Entry Simulator (SPES)

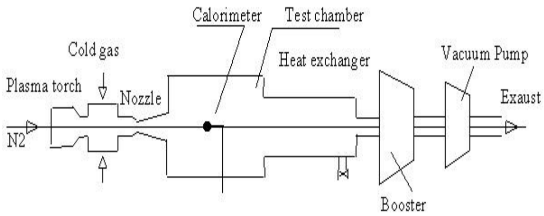

Fig. 11. Scheme of the Plasma Wind Tunnel SPES

Detailed description of the facility and related instrumentation and measurement techniques can be found in [3].

Tests are made using argon as plasma gas, at moderate levels of total enthalpy**.** Methods for predicting stagnation-point heat transfer in ionized gases are a difficult matter [4], therefore the simplified method proposed by Zoby [6] will be used hereinafter. Zoby suggests an empirical relation in the form :

$$\dot{q} = K \cdot H \cdot \sqrt{p_s / R_{eff}} \qquad (4)$$

Where total enthalpy and pressure are evaluated using data taken during the test, as hereinafter explained, R_{eff} can be assumed as 2.9 times the body radius as stated by Pope [7]. The thermo-chemical state of the arc-heated gas from reservoir pressure was determined quite easily by the frozen sonic flow method [7]. This procedure solves a one-dimensional steady inviscid flow. Effect of ionization has been accounted.

Table 1 shows some measurements and the results of the calculations based on this simplified approach.

Table 1

$\dot{m}_g$ = 0.5 [g/s]	$\dot{m}_g$ = 1.0 [g/s]
ΔV I = 3,75 [KW]	ΔV I= 5 [KW]
T_N = 2515 [K]	T_N = 2447 [K]
P_N =1558 [Pa]	P_N= 3072 [Pa]
ρ_N = 5.3 e^{-5} [Kg/m^3]	ρ_N = 1.2 e^{-4} [Kg/m^3]
V_N = 3339 [m/s]	V_N = 3295 [m/s]
M_N = 3,6	M_N = 3,6

The net total enthalpy of the flow *H* is calculated by the energy balance method. Stagnation temperature can be easily computed from *H*. The stagnation pressure can be calculated using the stagnation temperature at the sonic throat using the well known relation existing between mass flow rate, stagnation pressure and stagnation temperature. The exit Mach number can be then calculated using the one-dimensional theory by the ratio between the measured static pressure at the exit and the previously calculated stagnation pressure. Static temperature, density, dynamic pressure and Reynolds number can be calculated from the Mach number.

As shown in the Figs. 12-15, the tests in SPES has been made keeping the mass flow constant and modifying the current value from 150 to 200 [A]. These results show that, both in the first and second case, the curves deviate from each other in the low gas flow zone, and approach in the increasing gas flow zone. The heat-flux values predicted with the Zoby formula are shown together with the experimental points.

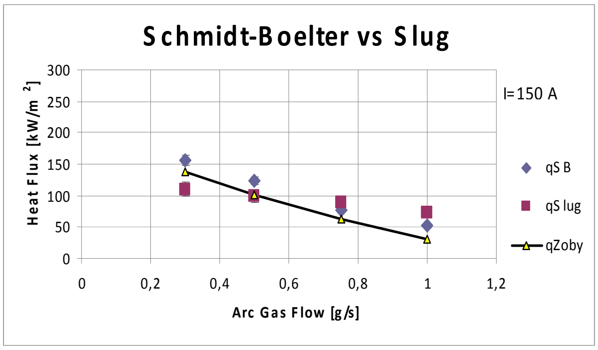

Fig. 12. Slug versus S-B sensors in SPES

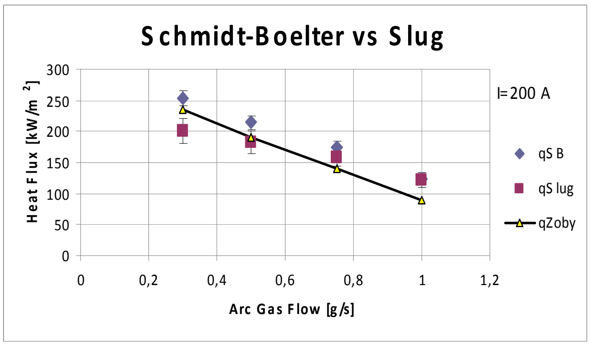

Fig. 13. Slug versus S-B sensors in SPES

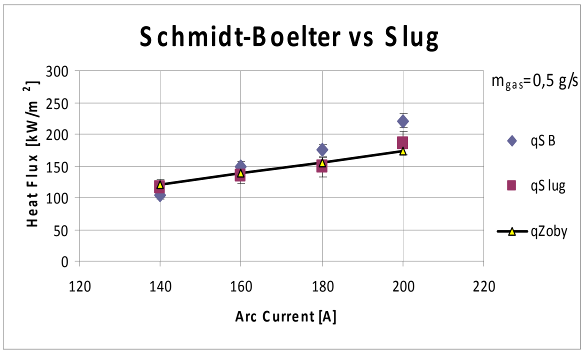

Fig. 14. Slug versus S-B sensors in SPES

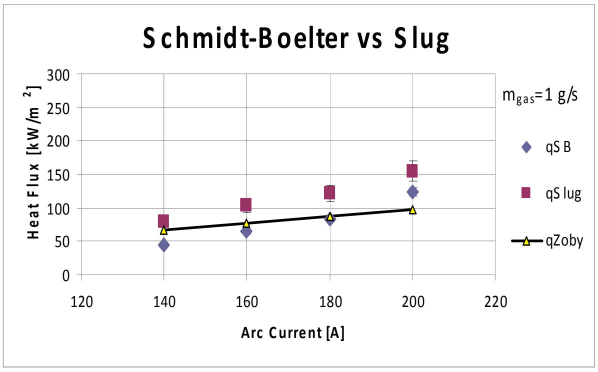

Fig. 15. Slug versus S-B sensors in SPES

Fig. 12 shows divergence of measured heat fluxes between 10% (at low heat fluxes) and 30% (at high heat fluxes) for an imposed arc current of 150[A] whilst Fig. 13 shows divergence of measured heat fluxes between 10% (at low heat fluxes) and 20% (at high heat fluxes) for an imposed arc current of 200[A]. Fig. 14 shows divergence of measured heat fluxes between 10% (at low heat fluxes) and 20% (at high heat fluxes) for an imposed Argon flow rate of 0.5[g/s] whilst Fig. 15 shows divergence of measured heat fluxes constantly around 25% at all heat fluxes for an imposed Argon flow rate of 1.0[g/s]. Observing Fig. 12-15 we can conclusively see that the curves deviate from each other while increasing the arc current value. This behavior could be explained by the modified sensor response due to the different ratio between radiative and conductive heat fluxes.

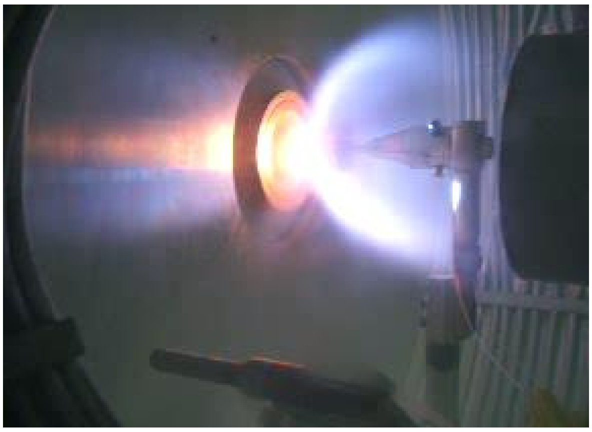

Fig. 16. Sensor tested in SPES

3.2 Using the slug sensor in an industrial plasma wind tunnel

A complete calorimetric probe was built, in a scale suitable to perform a test in PWT "SCIROCCO" of CIRA. In Fig. 17 the prototype of the probe tested in "SCIROCCO" is shown.

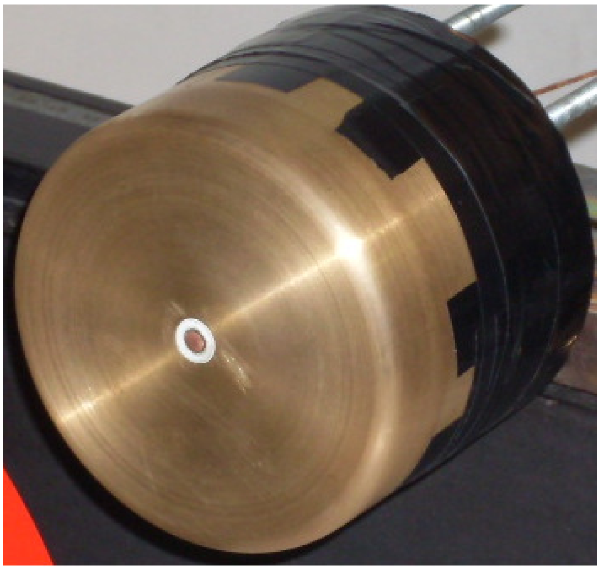

Fig 17. Calorimetric probe tested in PWT "SCIROCCO"

The material used as insulation is mullite while the body metal is brass. For the test in PWT a single thermocouple was used for measuring the temperature on the rear surface of the slug. The probe was housed in the SCIROCCO Test Chamber, Fig. 18, and mounted on the CIRA facility model support arm.

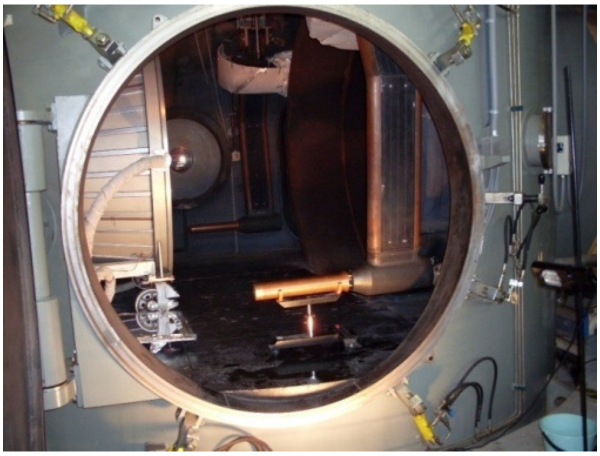

Fig 18. Probe mounted in the Test Chamber

Test condition are:

- Gas: Air
- p_s: 11 [mbar]
- H_0: 13.1 [MJ/kg]

Where p_s is the pressure downstream the shock wave, on the stagnation point of the probe, H_0 is the specific total enthalpy of the hypersonic flow. Fig. 19 shows the temperature trend of the slug during the insertion of the probe into the plasma flow in SCIROCCO.

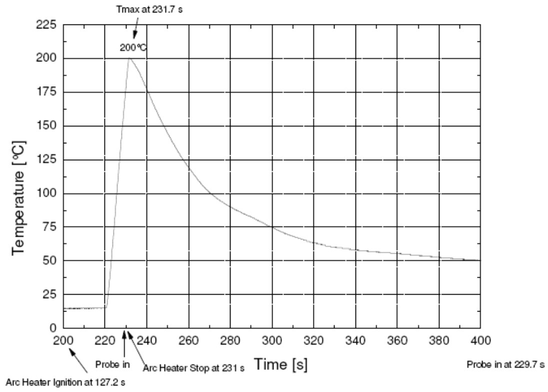

Fig. 19. Temperature-time curve of the slug

During the heating phase the temperature increase is linearly versus time, and the temperature gradient is $(\Delta T/\Delta t)$=17.5[°C/s], and the value of heat flux is 621[kW/m^2]. The hemispherical copper cooled probe of PWT SCIROCCO is instrumented with a Gardon gauge at the stagnation point and it is used to perform the measurement of stagnation point heat flux during each test. In this case it measured 963[kW/m^2].
Due to the fact that the Gardon gauge is mounted on a spherical surface whilst the slug has a flat face, in order to perform a comparison between these two results, the values of the slug have been corrected by means of an equivalent radius of curvature. In literature the issue has been studied by both Zoby [6] that by Pope [7].
In particular Pope obtained an equivalence, in terms of stagnation point heat flux, between a flat faced probe and a spherical faced probe, as $R_{eq}=2.9\ r_b$, where r_b is the radius of the basis of the flat face.
Taking into account that the stagnation point heat flux is dependent on the radius of curvature as follows:

$$\dot{q} \propto \frac{1}{\sqrt{R}} \tag{5}$$

It could be estimated:

$$\dot{q}_{eq\_spherical} \approx 1.7 \cdot \dot{q}_{slug\_flat\_faced} \tag{6}$$

By this correlation, the heat flux that can be compared with the one measured by the Gardon gauge is:

$$\dot{q}_{slug\_flat\_faced} = 1055\left[kW/m^2\right]$$

The values that were measured are affected by uncertainties of measurement. The uncertainty in the assessment of heat flow of the slug, neglecting at first analysis the density and the specific heat, (as they are constants given with extreme accuracy in the literature), can be derived estimating the uncertainties on l and on $\Delta T/\Delta t$. Regarding the length of the slug, l, the uncertainty of the caliper used for the measurement is estimated of ±0.1mm, while the temperature gradient, $\Delta T/\Delta t$ has an estimated uncertainty of ±1[°C/s]. Using these values we get a percentage of the uncertainty of ±5.5%. For the Gardon gauge the uncertainty of heat flux is assumed to be ±90 [kW/m^2]. Summarizing, we have:

- $\dot{q}_{eq\_spherical\_slug} = 1055 \pm 58 \ \left[kW / m^2\right]$
- $\dot{q}_{gardon\_gauge} = 963 \pm 90 \ \left[kW / m^2\right]$

which show an interval of overlap between the two data.

3. THEORY OF THE SLUG-TYPE SENSOR FOR VARYING HEAT FLUX

3.1 Introduction

Generally speaking, in a program of reentry heat-transfer investigations the problem of heat rate measurement requires a sensor capable of absorbing high heat rates over relatively long periods of time. If a slug calorimeter is used, the material must have enough thermal capacity to prevent melting during the test period. Thus the slug must be relatively thick since it will experience large temperature gradients. These requirements, plus the variation of the thermal properties of the slug with temperature, have made the measurement difficult to treat simply and have resulted in the use of complex and time-consuming techniques. Since most methods used for determining high heat rates of long duration require multi-temperature measurements and curve-fitting procedures, an effort was made to find a method that would simplify the instrumentation and data reduction.

3.2 Theory

For the case of one-dimensional heat flow, the calorimeter is considered to be a solid bounded by a pair of parallel planes at $x = 0$ and $x = l$. The solid is heated uniformly at $x = l$ with a constant input and with no heat loss. The well-know solution of Carslaw and Jaeger [8] for the temperature field, when time becomes large enough, reduces to the Eq.1.

Following McDonough and Youngbluth, [9], if an average or effective temperature could be determined and shown to occur at a particular location in the calorimeter, a temperature measurement made at this point would yield an average specific heat to be used in the Eq. 1. This measurement can be made when the specific heat is a linear function of temperature over the range established by the temperature gradient in the calorimeter. If the average temperature is changing at an average rate (average dT/dt), enough data are obtained at this point to determine the correct heat flux after allowing for transient effects to subside and assuming that ρl is essentially constant. McDonough and Youngbluth shows that the time derivative of the average temperature is a constant, independent of time, and after the transient period is over, the time derivative of this average temperature is independent of position. The location of the average temperature is :

$$x = 0.578 \cdot 1 \approx 0.6 \cdot 1 \qquad (7)$$

as measured from the back face of the calorimeter. A thermocouple at this point will give the correct temperature needed to find the c and dT/dt to be used in the Eq.1. In determining the location of the average temperature and the average rate of change of temperature, the thermal parameters were assumed to be constant with temperature. Because of the requirement that the transient disappear before valid data can be obtained, a characteristic minimum response time is necessary to predict the calorimeter performance. Such a time may be defined as:

$$\tau = \frac{2l^2}{\pi^2 \alpha} \qquad (8)$$

Since α is a function of temperature, the actual response time of the calorimeter depends on the temperature rise during the transient period which in turn depends on the input. In every application, care should be taken to consider the temperature sensitivity of the particular slug material and the expected input when estimating the response time of the calorimeter.

3.3 Limits of the proposed method

The usefulness of the method which simply utilizes Eq.1, depends on certain conditions which should be carefully examined. The conditions are as follows:

(1) The variation of thermal diffusivity with temperature must be such that the average temperature and average dT/dt occur at a single fixed point.

(2) The average temperature must define the average specific heat of the calorimeter.

(3) The losses are small.

The first condition is necessary because single-point temperature measurements are used to describe the behavior of the entire calorimeter. The average temperature is used to determine the average or effective value of c. Since a thermocouple indicates the temperature at a fixed point, the average temperature must remain at this point or the determination of c will be in error. Similarly, the average or the effective value of *dT/dt* must remain at this same point. The location of the average temperature and the average *dT/dt* was found to be at approximately *0.6 l* as measured from the back face of the calorimeter.

For the average specific heat to be determined by the average temperature of the calorimeter, the specific heat should vary linearly with temperature. If this is not true, these average values will not occur at the same location in the calorimeter, and the use of a single thermocouple may not suffice. Each material considered should be investigated thoroughly to determine its suitability for the intended application.
Because Eq.1 indicates the thermal-energy storage rate, the heat loss should be small to retain accuracy. The shape and the magnitude of the temperature gradient in the calorimeter depends upon the magnitude of the thermal diffusivity and its variation with temperature. If the losses become so excessive that they affect the shape of the temperature gradient curve, the location of the average values of *T* and *dT/dt* will change.

4. USE OF THE SLUG SENSOR FOR VARYING HEAT FLUX

In order to verify the results from McDonough and Youngbluth theory, a thick OFHC copper slug, ϕ=*10[mm], l=10[mm],* was equipped with a single thermocouple located at 60% from the back face, see Fig.20.

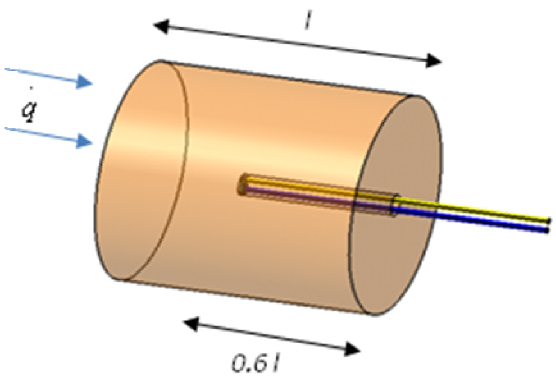

Fig 20. Single thermocouple thick slug sensor

The variable heat flux was experimentally obtained by varying the arc current from an higher initial value to a final value corresponding to the wanted flow energy whilst the slug sensor was in the flow.

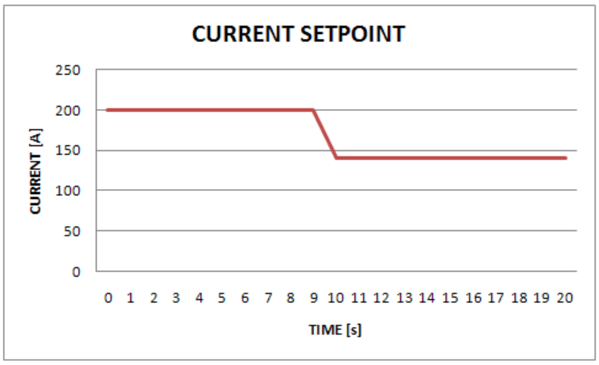

Fig 21. Current Setpoint

In order to quantify the duration of the transient between two current setpoints, the same test has been repeated using either the slug either the Schmidt-Boelter sensor.

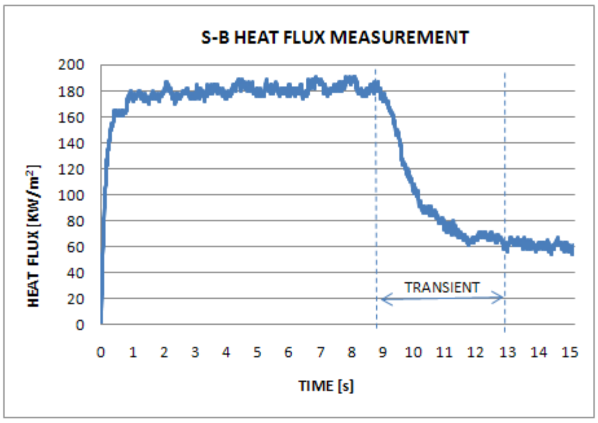

Fig 22. Heat flux measurement (Schmidt-Boelter)

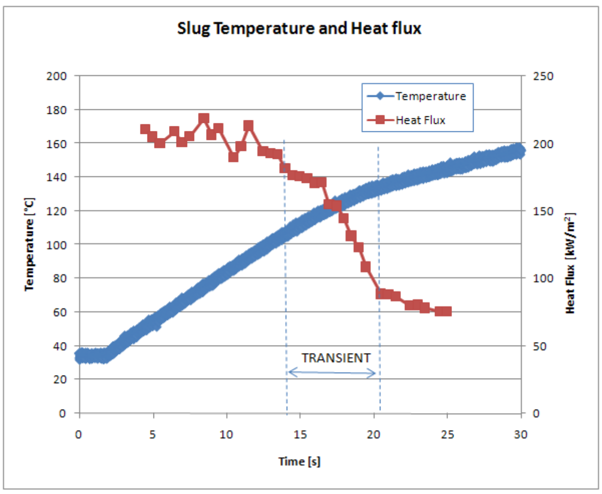

Fig 23. Heat flux measurement (Slug)

For the S-B the electrical signal was directly converted in heat flux dividing by the sensor sensitivity which is 0,154 mV/KW/m^2 whilst for the slug the heat flux was obtained by multiplying by *ρcl* the *dT/dt* obtained graphically from the experimental temperature-time curve.
Figs. 22-23 show that Slug and S-B are both following in real time the heat flux variations with reasonable agreement.

5. CONCLUSIONS

It has been experimentally shown that the output of a single thermocouple, placed at 60 percent of the length from the back face, in thick slug calorimeters can yield sufficiently accurate measurements of both constant and varying high heat fluxes.

Since the time response is determined by the length of the calorimeter and the thermal diffusivity, which varies with temperature, the calorimeter response will change with temperature. The material and size of the calorimeter would depend upon the test conditions and the requirements of the experiment. Since this approach requires the installation of only one thermocouple per calorimeter, this technique can greatly simplify the problems of data acquisition and data reduction in high heat-rate investigations particularly in flight applications requiring a large number of calorimeters.

6. ABBREVIATIONS AND ACRONYMS

A = Area of the front surface of the slug
c = Specific heat
ΔT_{mp} = Necessary temperature difference to reach the melting point
Δt_{mp} = Necessary time difference to reach the melting point
ΔV = Arc voltage
ϕ = Slug diameter
H = Total enthalpy
K = Zoby [6] constant= 165 [g/(cm$^{3/2}$ s atm$^{1/2}$)]
k = Thermal conductivity
l = Slug length
M = Mass of the slug
M_N = Mach number at nozzle exit
$\dot{m}_g$ = Gas mass flow rate
P_N = Pressure at nozzle exit
p_s = Stagnation-point pressure
$\dot{q}$ = Local heat flux
R_{eq} = Equivalent radius in terms of heat flux
R_{eff} = Effective body nose radius
r_b = Radius of the basis of the flat face
ρ = Density
ρ_N = Gas density at nozzle exit
T = Temperature
T_N = Temperature at nozzle exit
t = Time
V_N = Gas velocity at nozzle exit

REFERENCES

1. *Standard Test Method for Measuring Heat-Transfer Rate Using a Thermal Capacitance (Slug) Calorimeter*, ASTM E457-72, Reapproved 2002.

2. Schultz D. L. and Jones T. V., *Heat-Transfer Measurement in Short-Duration Hypersonic Facilities*, AGARD graph No.165

3.Zuppardi G. and Esposito A., *Blowdown arc facility for low-density hypersonic wind tunnel testing*, Journal of Spacecraft and Rockets, Vol. 38, N.6, pp 946-948, Nov-Dec. 2001.

4. A. Esposito, F. De Rosa, F. De Filippis, A. Martucci, E. Graps, E. Trifoni "A new concept of heat-flux probe for the Scirocco Plasma Wind Tunnel" 16th AIAA/DLR/DGLR International Space Planes and Hypersonic Systems and Technologies Conference, Bremen, 2009 AIAA Paper 2009-7445

5. H. Coleman and W G. Steel "Experimentation and Uncertainty analysis for engineers", Wiley Interscience, pp 42

6. E. V. Zoby, Empirical Stagnation-Point Heat-Transfer Relation in Several Gas Mixture at High Enthalpy Levels, NASA TN D-4799, 1968.

7. R.B. Pope, "Stagnation point convective heat transfer in frozen boundary layers", AIAA Journal vol. 6, n.4, April 1968, pp. 619-624.

8. Carslaw, H. S.; and Jaeger, J. C.: Conduction of Heat in Solids. Second ed., Oxford" Univ. Press, Inc., 1959

9. John F. McDonough and Otto Youngbluth, Jr.,"A simple method for determining high heat rates by using slug calorimeters" NASA TM X – 1408, 1966