DESIGN OF SLUG CALORIMETERS FOR RE-ENTRY TESTS

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1. INTRODUCTION

The paper deals with the design, manufacturing and test of “slug” calorimeters, both for ground testing as for dynamic and flight testing where the magnitude and duration of heating require a thick slug equipped with several thermocouples due to the appreciable internal temperature gradients. It is discussed the possibility of using a single thermocouple application on thick slug calorimeters subjected to heating rates in the range from 50 to 250 [kW/m^2] keeping an acceptable engineering approximation. In fact, it has been found that the equation:

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

where ρ, c and *l* are respectively density, specific heat and length of the slug, for a thick OFHC Copper calorimeter yields 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 length, this condition held true for a variety of inputs, both constant and varying. This method, requiring a single-point measurement per calorimeter, substantially reduces time and costs involved in investigations of both varying and constant high heat fluxes .

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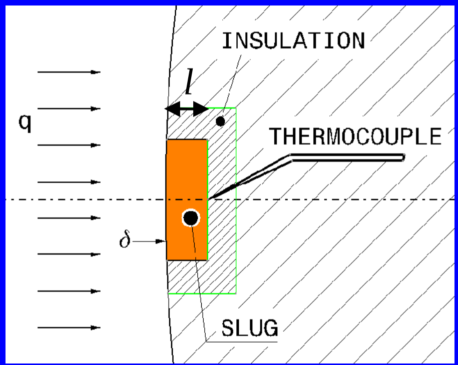
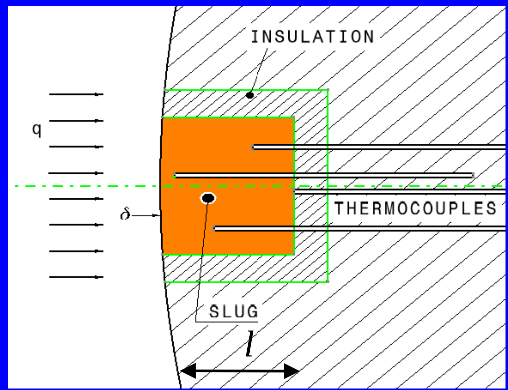
2. SLUG BASIC THEORY

The slug-type heat-flux sensor consists of a small cylinder of metallic material (slug) fitted into the exposed face of the model but isolated from it to minimize the heat losses to and from the model in order to approximate the heat transfer as one-dimensional.

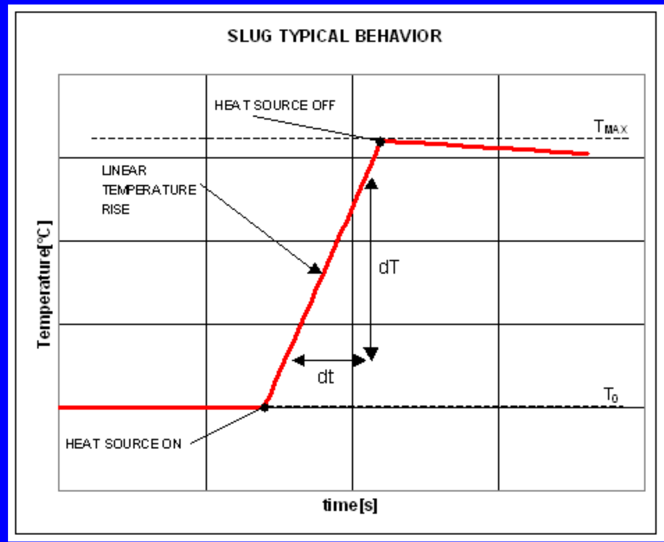


$$\dot{q} = \rho \cdot c \cdot l \cdot \frac{dT}{dt} \qquad \text{(Eq.1)}$$



In case of thin slugs with non-significant temperature gradients a single thermocouple located on the rear surface of the slug is sufficient to measure the temperature

In case of thick slugs with significant temperature gradients several thermocouples located in different positions are needed to monitor the temperature itself



The measurement of a constant heat flux is performed starting from a reference temperature, then the sensor is inserted into the stream. After a short initial transient the temperature increases linearly versus time allowing for temperature tracking for a time sufficiently long to enable accurate determination of the derivative *dT/dt* but not too long to not compromise the physical integrity of the sensor. At this point the sensor is removed from the flow continuing to acquire temperature data.

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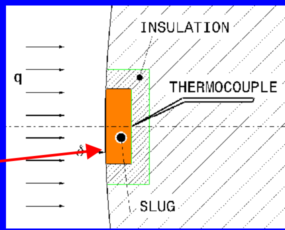
3. SLUG DESIGN PRINCIPLES

The choice of the material used to build the slug involves several considerations but the key role is played by the melting temperature of the exposed surface.



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. In this situation the relationship between the heat flux and the temperature of the back surface becomes very complex. 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. The time required to achieve the melting, t_{mp}, is obtained in the following formula:

$$\Delta t_{mp} = \frac{\pi \cdot k \cdot \rho \cdot c \cdot \Delta T_{mp}^2}{4\dot{q}^2} \qquad \text{(Eq.2)}$$

Materials with high values of k, ρ, c and ΔT_{mp} allow, under the same heat flux, for longer exposure to flow (ΔT_{mp} is the necessary temperature increase to reach surface melting).
Copper is typically a good compromise for its low cost (compared to other materials), easy machinability and large availability.

Element / Material		T_{mp}	k	ρ	c	k ρ c T_{mp}
Symb	Name	[°C]	[W m^{-1} °C^{-1}]	[kg m^{-3}]	[J kg^{-1} °C^{-1}]	[W^2 s m^{-4} °C^{-1}]
Pb	Lead	328	35,3	11350	130	1,71E+10
	Inconel 625LCF	1290	9,7	8440	410	4,33E+10
	Steel 661	1300	12,3	8250	435	5,74E+10
	Inconel 600	1355	14,9	8470	444	7,59E+10
Ti	Titanium	1660	21,9	4540	520	8,58E+10
	Steel 302	1400	16,2	7860	500	8,91E+10
Zn	Zinc	420	116,0	7130	390	1,35E+11
Ta	Tantalum	1996	57,5	16650	140	2,68E+11
	Brass CuZn40Pb2	850	111,0	8430	380	3,02E+11
Pt	Platinum	1772	71,6	21450	130	3,54E+11
Al	Aluminum	660	237,0	2702	900	3,81E+11
Re	Rhenium	3180	47,9	21040	130	4,17E+11
Fe	Iron	1535	80,2	7874	440	4,27E+11
Ni	Nickel	1453	90,7	8900	440	5,16E+11
C*	*Graphite	3500	129,0	2260	710	7,24E+11
Os	Osmium	3027	87,6	22600	130	7,79E+11
Au	Gold	1065	317,0	19320	128	8,35E+11
Be	Beryllium	1278	201,0	1848	1820	8,64E+11
Mo	Molybdenum	2617	138,0	10220	250	9,23E+11
Ag	Silver	961	429,0	10500	235	1,02E+12
Cu	Copper	1085	401,0	8960	380	1,48E+12
W	Tungsten	3407	174,0	19350	130	1,49E+12
C**	**Diamond	3547	2200,0	3500	630	1,72E+13

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3. SLUG DESIGN PRINCIPLES cont'd

Slug material vs application:

$$\Delta t_{mp} = \frac{\pi \cdot k \cdot \rho \cdot c \cdot \Delta T_{mp}^2}{4\dot{q}^2} \quad \text{(Eq.2)}$$

Case 1) Re-entry flight. Slugs annealed into thermal shield. Key factors are:

- **Weight of calorimeters**
- **Weight of wiring**
- **Cost of raw materials and fabrication**
- **Cost of payload ($/kg)**
- **Slugs are typically non-reusable**

Case 2) Re-entry lab test. Slugs annealed into a probe or scaled proto. Key factors are:

- **Cost of materials and fabrication**
- **Slug are typically re-usable**

Element / Material		T_{mp}	k	ρ	c	k ρ c T_{mp}
Symb	Name	[°C]	[W m^{-1} °C^{-1}]	[kg m^{-3}]	[J kg^{-1} °C^{-1}]	[W^2 s m^{-4} °C^{-1}]
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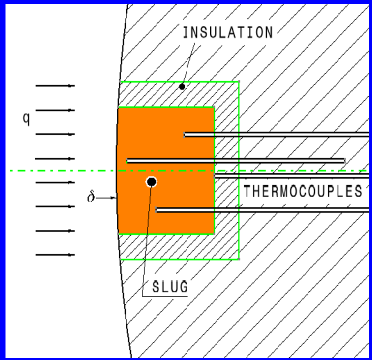
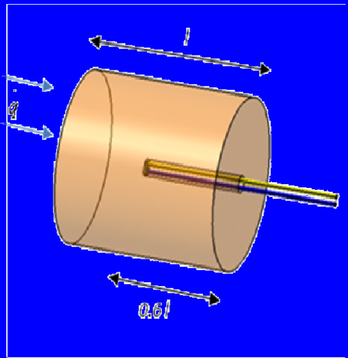
4. SLUG THEORY FOR CONSTANT AND VARYING HEAT FLUXES

For the one-dimensional heat flow case, 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, see paper ref [8], for the temperature field reduces to the Eq.1 when time becomes large enough. Following McDonough and Youngbluth, see paper ref [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 a reliable average dT/dt 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. It can be proven theoretically and has been hereinafter proven experimentally that the location of the average temperature is given by the Eq.3 as measured from the back face of the calorimeter.



MULTI-TC*



SINGLE-TC*

Define T_{AV} along the slug

$$x \approx 0.6 \cdot l \qquad \text{(Eq. 3)}$$

It can be also proven that the time derivative of the average slug temperature is a constant and after the transient period is over, it is independent of position along *l*. 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 in Eq.4. 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 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.

$$\tau = \frac{2l^2}{\pi^2 \alpha} \qquad \text{(Eq. 4)}$$

(*TC=Thermocouple)

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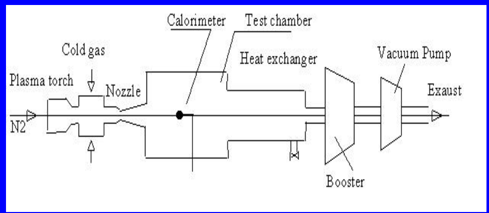
5. SINGLE-THERMOCOUPLE THICK SLUG vs SCHMIDT-BOELTER (CONSTANT HEAT FLUX)

In order to validate the heat flux measurement made by the thick single-thermocouple Slug, the test matrix covered using the Slug itself was repeated measuring the heat fluxes by a Schmidt-Boelter calibrated probe. The Slug calorimeter was hand-crafted in laboratory as a cylinder of OFHC copper *ϕ=10[mm], l=10[mm]*. The insulation is a low-conductivity ceramic. A Chromel-Alumel (K type) thermocouple is soldered at 60% of its length as previously shown. The Schmidt-Boelter gauge used is the SBG01-200 model from Hukseflux.



SMALL PLANETARY ENTRY SIMULATOR

SPES FACILITY AT UNIVERSITY OF NAPLES

$\dot{m}_g$ = 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

SPES TYPICAL FLOW PARAMETERS

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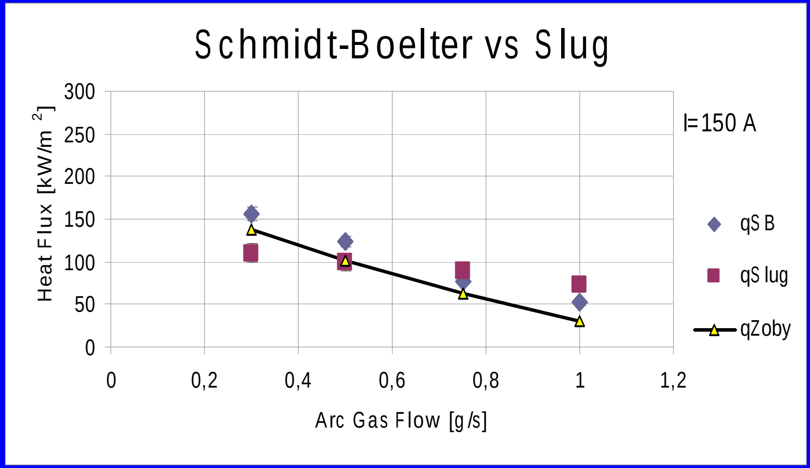
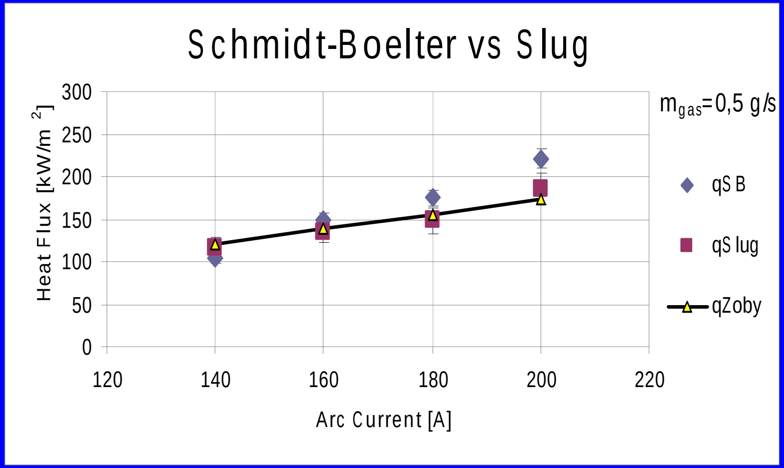
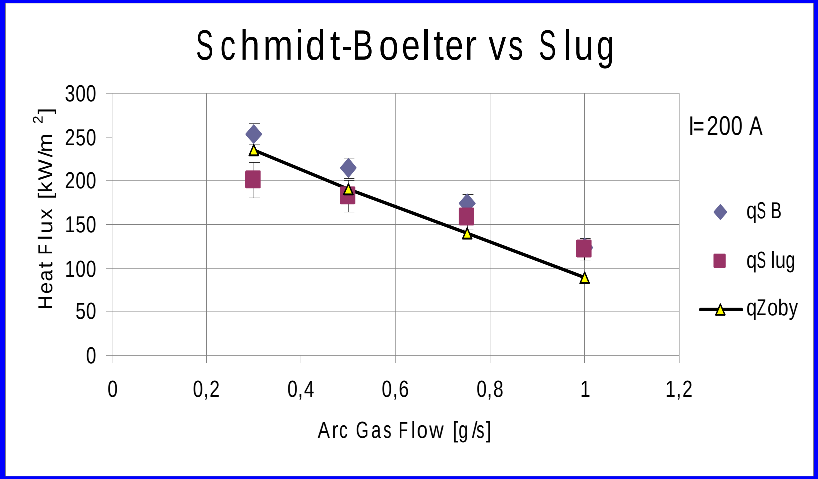
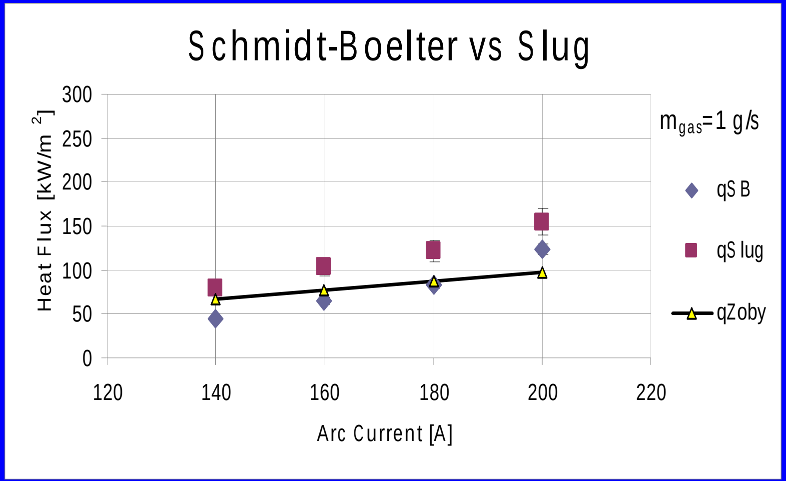
5. SINGLE-THERMOCOUPLE THICK SLUG vs SCHMIDT-BOELTER (CONSTANT HEAT FLUX) cont'd

Most significant results are hereinafter show for steady heat flux.









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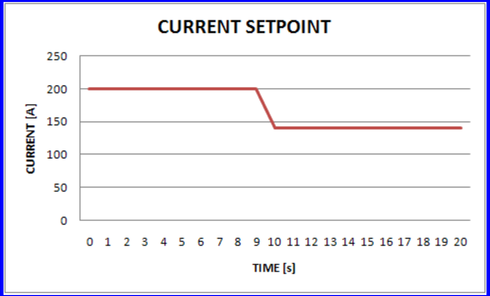
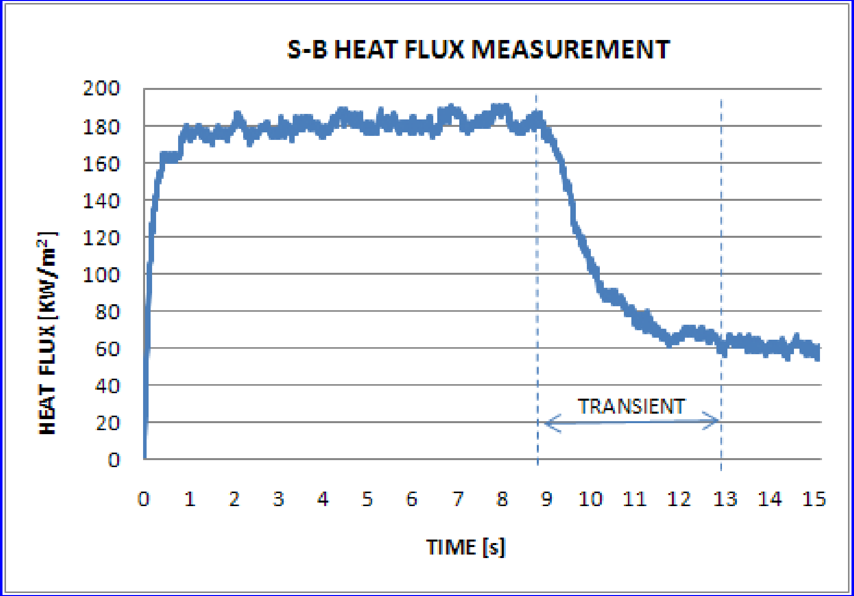
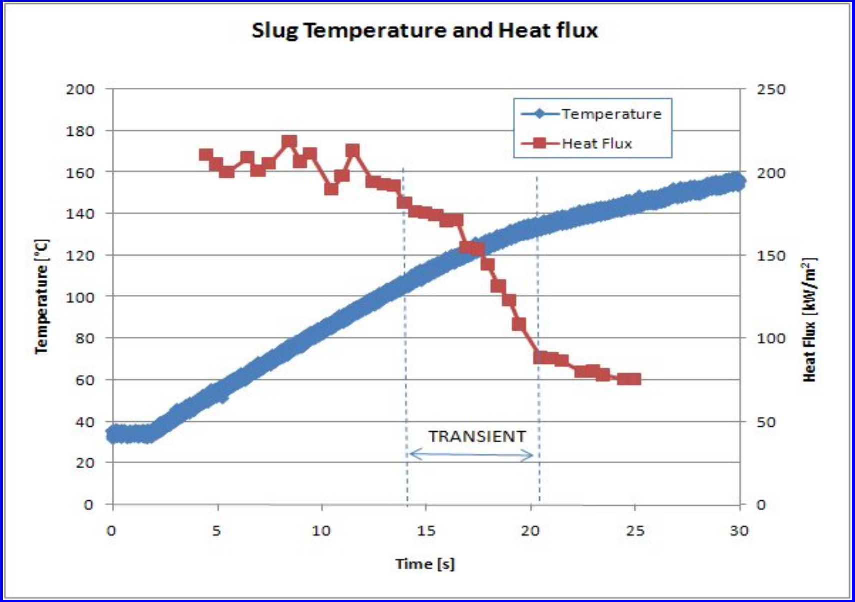
6. SINGLE-THERMOCOUPLE THICK SLUG vs SCHMIDT-BOELTER (VARYING HEAT FLUX)

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. 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. 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.

Most significant results are hereinafter show for steady heat flux.







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7. CONCLUSIONS

It has been experimentally shown that the output of a single thermocouple, placed at 60 percent of the length from the back face of thick slug calorimeters made out of OFHC Copper can yield sufficiently accurate measurements of both constant and varying high heat fluxes in the range from 50 to 250 [kW/m^2].
Results achieved by this method were in agreement to within 10% of both those made using a calibrated Schmidt-Boelter gauge and those obtained numerically.
Since the time response is determined by the length of the Slug and the thermal diffusivity, which varies with temperature, the calorimeter response is temperature dependant and therefore the relevant material and size must be defined upon test conditions and experimental requirements. Since this approach requires the installation of only one thermocouple per calorimeter, it simplifies the data acquisition particularly in flight applications (Thermal Shield) requiring a large number of calorimeters under very high heat fluxes (currently under development and object of our current and future activity).