Closed gap slug calorimeter for plasma stream characterization

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Slug calorimeters are used in sheer and stagnation mode to characterize heat flux levels for high enthalpy streams. The traditional design features a gap between slug and holder, which can be of concern in these convective heat flux environments. The challenge is to develop a calorimeter that closes the gap to gas flow, but largely maintains thermal insulation of the slug. The work presented herein introduces two new slug calorimeter designs featuring a closed gap. This is done using either aerogel as a filler or press fitting the slug with a disk. The designs were verified and compared to the baseline calorimeter design under radiative heat flux. Building on this, the calorimeters were exposed to convective heat flux in the arc-jet facilities. Results from the new designs and conclusions on the impact of the gap in convective heat flux will be shown.

I. Nomenclature

c_p	=	specific heat, *J/kg-K*
k	=	thermal conductivity, *W/m-K*
$\dot{q}$	=	heat flux per unit area, *W/cm²*
ρ	=	density, *kg/m³*
T	=	temperature, *Kelvin (K)*

II. Introduction

Slug calorimeters are used to determine heat flux for a wide range of applications, including radiative and convective heat flux. Their working principle is based on monitoring the temperature change ΔT induced in a slug – a cylindrical oxygen free copper element - with density ρ and specific heat c_p over the time t. The heat flux $\dot{q}$ assumes that all incident heat flux is absorbed at the slug surface, and that the heat conduction through the slug can be treated as a one dimensional problem.

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$$\dot{q} = \rho c_p \frac{\Delta T}{\Delta t}$$ **Equation 1**

For testing in high enthalpy streams such as in the arc jets at NASA Ames Research Center (ARC), slug calorimeters are used to characterize cold wall heat flux conditions on the test article. For this, the slugs are mounted in copper bodies matching the geometry of the test article.

In the past, different slug calorimeter designs have been tested. The design currently used at NASA ARC is shown in Fig.1 and is a result of a round robin study investigating designs in 1964[1]. These slugs are routinely used at ARC in stagnation, and have recently also been tested under sheer flow conditions[2].

When exposing a slug calorimeter to high enthalpy conditions, uncertainties in measurement arise from catalytic effects on the slug surface, the gap between slug and holder, and heat loss from the slug. The gap between slug and holder is of concern, since on the one hand the possibility of gas flow due to pressure differences along the gap cannot be excluded. On the other hand, once the gas has entered the gap, it will aid in conductive losses from slug to holder. In the paper presented here, the effects on heat flux measurements from the gap between slug and holder are studied under stagnation and sheer flow conditions. This is done by introducing two new designs for closed gap calorimeters and comparing their results to a baseline calorimeter of the traditional design. In addition, tests performed under a quartz lamp bank are used to verify evaluation methods for these three slug calorimeter designs.

III. Experimental Setup

The three slug designs under investigation are shown in Figure 1 and will be discussed below in more detail. Two of these designs feature a closed gap, hence preventing plasma from entering between slug and holder and adding to the uncertainty of heat flux determination.

Figure 1. All three slug calorimeters under investigation (post test).

A. Heat Flux Source and Setup

All three slug calorimeter designs were tested in the arc jet facilities in stagnation flow at two different conditions and in sheer flow. Additionally, tests using a halogen lamp were conducted to verify evaluation techniques, absolute values and repeatability of the calorimeters.

1. Quartz Lamp Bank

The quartz lamp bank (Precision Control Systems Inc. Heat Flux Calibrator) is shown in Figure 2. It consists of a total of 15 quartz lamp tubes arranged horizontally in an array. This yields a uniformly heated area of 20.32cm in diameter at a distance of 7.62cm from the lamp array. Its nominal heat flux is 47W/cm^2 (100%). For the experiments presented here, the quartz lamp array is suspended by three adjustable rods. The sensors under investigation are embedded in a Sulfrax™ block because of its high reflectivity, melting temperature and low thermal conductivity. An electric substitution radiometer (Kendall MK IX) serves as the reference for measuring absolute heat flux values. A gardon gage is used as a transfer reference, due to its simplicity in handing compared to the radiometer.

As seen in Figure 2 the Sulfrax™ block is mounted on a sledge and is horizontally positioned under the lamp array.

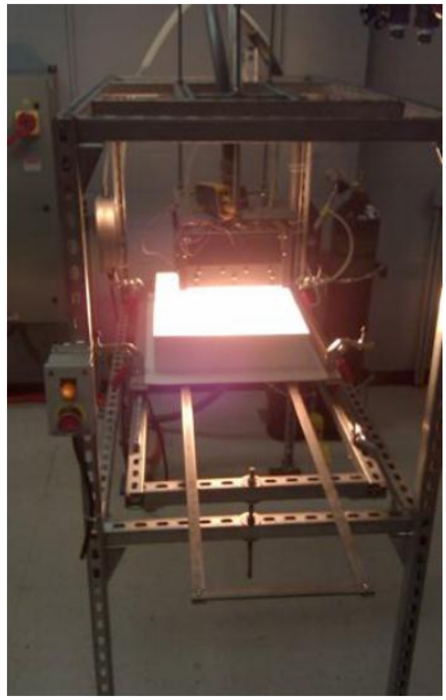

Figure 2. Quartz lamp bank in operation.

2. Arc-Jet Facilities

In order to study the impact of the gap on convective heat flux measurements, the calorimeters are exposed at two different conditions in stagnation and sheer flow. The 20MW aerodynamic heating facility (AHF) was used for this purpose. This facility is documented in literature[3].

B. Slug Calorimeter

In this section the three slug calorimeter designs compared are introduced and will be discussed in the final paper. The size and shape of the slug itself is for use in a flatface calorimeter body and is identical - regardless of the holder design described in the following.

1. Baseline Slug Calorimeter

This is the calorimeter typically used at ARC. It is documented in literature[4] and shall be just briefly summarized within this paper. Figure 3 shows a cross section. Three ruby balls from the side and three from the bottom suspend the slug. The gap between slug and holder is 0.254mm.

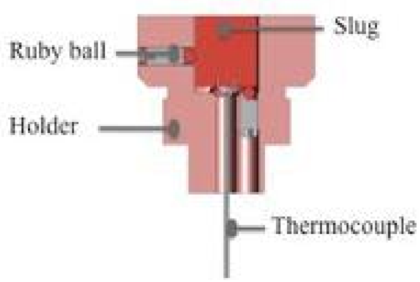

Figure 3. Slug calorimeter typically used at NASA ARC.

2. Silica Aerogel Slug Calorimeter

A picture of the calorimeter using silica aerogel composite and its cross section is shown in Figure 4. Aerogel composite was used because of its intrinsically good thermal insulation properties. The silica aerogel composite used was provided by the Aerogel Laboratory at the Jet Propulsion Laboratory. The composite is made up of silica aerogel, titania powder, silica powder and glass fiber felt[5] . Silica aerogel composite rings were cast to approximate size and then machined to the desired dimensions. The cross section shows how the silica aerogel ring is seated snugly between slug and holder. Previous tests in the arc-jet facilities have shown that it recesses when large areas come in direct contact with the plasma.

Thus, a copper disk shields the aerogel composite surface from plasma exposure, leaving a 0.1524mm gap between disk and slug– half the size of the baseline design. The covering disk is held in place by setscrews. Apart from this modification, the slug calorimeter is assembled much in the same way the reference calorimeter is, using ruby balls to hold and insulate the slug.

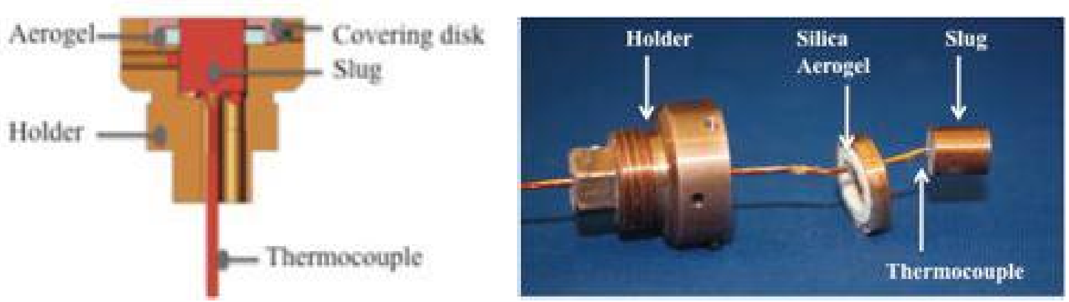

Figure 4. Silica Aerogel Slug Calorimeter Design.

3. Press Fitted Slug Calorimeter

A picture of the press fitted slug calorimeter and its cross section is shown in Figure 5. The slug is press fitted into a copper disk with tapered inside edges to minimize heat loss through conduction. This connection is strong enough to hold the slug in place, and makes ruby balls unnecessary. The disk is secured into the holder through setscrews.

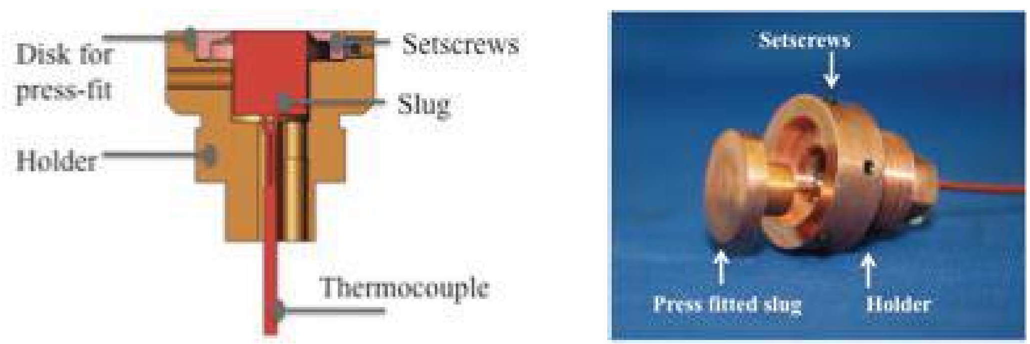

Figure 5. Press fitted slug calorimeter design.

This press fitted design allows the gap to be completely closed at the surface, making polishing and handling easier. The thickness along which it is press fitted is about 0.1016mm along the diameter (resulting in an area of 2.5mm^2). The disk is fixed in place within the holder by setscrews.

C. Test Matrix

First, repeatability and consistency of heat flux values under radiant heat flux in the quartz lamp bank was evaluated. Further, two tests for stagnation flow were carried out on all three slug calorimeter configurations. In addition, a wedge test was performed. To ensure repeatability, the slug calorimeter was rebuild before each test and evaluated afterwards.

IV. Data Reduction Methodology

For the reduction of data, this paper will use the method described in ASTM[6]. In this paper, the question of insertion time into the arc jet stream and influence of heat loss due to the gap in the current slug design will be investigated.

V. Results

Differences between baseline and newly designed slug calorimeters in response to convective heat flux will be shown. Radiant heat flux tests are expected to show comparable results between all three designs, verifying the evaluation method used. This new design will allow one of the sources for uncertainty in high enthalpy heat flux measurements to be eliminated.

VI. Acknowledgments

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VII. References

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