Development of Graphite Heat Flux Gauge

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***Abstract*—Heat Flux measurement plays a vital role in design, development and qualification of thermal systems. Surface substrate properties, convective and radiative environments determine the choice of sensor for measuring Heat Flux. A gauge was designed to measure heat flux in transient heating conditions using solder rod and oxy-acetylene flame as heat sources. Many materials were explored and finally graphite was chosen as the slug material due to its higher melting temperature and good thermal conductivity. Graphite was coated with Silicon Carbide to prevent oxidation.**

The coated graphite slug was insulated by ceramic insulation to prevent heat loss. The coated surface of the slug was exposed to heat; a K- type thermocouple was connected to the other end of the slug. DAS (Data Acquisition System) was connected to thermocouple to acquire data. Series of experiments were conducted and experimental data has been recorded. Heat Flux v/s Time and Slug Temperature v/s Time graphs were plotted.

Experimental results show that graphite senses heat satisfactorily at wide range of temperatures. Silicon Carbide coating was successful in preventing the oxidation of graphite. It is also clear from the experiment that graphite slug material with higher thermal conductivity responds better and hence yields better results.

***Keywords*—Heat Flux; Thermal Conductivity; Graphite Slug; K-type Thermocouple; DAS(Data Acquisition System); Ceramic Insulation**

I. INTRODUCTION

A. Overview

Most of the many methods for measuring heat flux are based on temperature measurements on the surface or close to the surface of a solid material. Usually this involves insertion of a device either onto or into the surface, which has the potential to cause both a physical disruption and a thermal disruption of the surface. As with any good sensor design, the goal for good measurements must be to minimize the disruption caused by the presence of the sensor. It is particularly important to understand the thermal disruption caused by the sensor because it cannot be readily visualized and because all heat flux sensors have a temperature change associated with the measurement. Consequently, wise selection of the sensor type and operating range is important for good heat flux measurements [1].

A heat flux sensor is a transducer that generates an electrical signal proportional to the total heat rate applied to the surface of the sensor. The measured heat rate is divided by the surface area of the sensor to determine the heat flux. Thermal sensors play a vital role in the design, development and qualification of thermal system and sub-systems. The heat flux can have different origins; in principle convective, radiative as well as conductive heat can be measured. Heat flux sensors are known under different names, such as heat flux transducers, heat flux gauges and also heat flux plates.

Apart from conventional sensors for measuring fluid or wall temperature, measurement of heat flux has become very common. A variety of techniques have been employed, both intrusive and non-intrusive to measure heat flux, flame and surface temperatures [2]. A heat flux sensor should measure the local heat flux density in one direction. The result is expressed in watts per square meter. .

B. Need for Heat Flux Gauge

Heat flux is a valuable input for any thermal system design as one can do away with

- The computation of heat transfer coefficient which are often calculated by using empirical relations.
- The measurement of fluid temperatures under actual operating conditions involving complicated probe design which are prone to large measurement errors especially at high temperature and high velocities.[3]
- Surface temperature measurements which involve costly and special instrumentation requirement.

The major application of these sensors is in the aerospace industry. These sensors are widely used in the qualification of thermal protective systems for aerodynamic and re-entry heating applications, satellite thermal control, base heating measurement and to qualify thermal protection materials used in combustion chambers and nozzles using plasma jet facility [4].

Thermal management of materials and temperature control of industrial processes is becoming more important in order to achieve higher quality standards. An example would be to monitor thermal stresses in aerospace applications.

Measuring heat flux gives additional information of where and how much thermal energy is being transferred or dissipated. Thus, maximizing and minimizing thermal energy transfer of many thermal systems in practical use is crucial to their optimum performance. The challenge is to measure heat flux using gauges to estimate above mentioned characteristics of a system.

Since, heat transfer is a primary input or boundary condition to several thermal problems the interest in its measurement will continue to grow. In the design of any thermal protection system or subsystem, the selection of material and its characteristic dimensions are primarily based on this quantity. The development of advanced aerospace vehicles further demand heat flux measurement with very high accuracy.

C. Heat Flux Measurement

Most of the many methods for measuring heat flux are based on temperature measurements on the surface or close to the surface of a solid material. Usually this involves insertion of a device either onto or into the surface, which has the potential to cause both a physical disruption and a thermal disruption of the surface. As with any good gauge design, the goal for good measurements must be to minimize the disruption caused by the presence of the gauge.

It is particularly important to understand the thermal disruption caused by the gauge because it cannot be readily visualized as all heat flux gauges have a temperature change associated with the measurement. Consequently, wise selection of the gauge type and operating range is important for good heat flux measurements [1].

Measurement of heat flux is important to know the total heat transferred through a specific area. In combustion chambers, the heat flux is instrumental in finding out specific design parameters such as the working area of the combustor, placement of flame holders

D. Slug Type Heat Flux Gauge

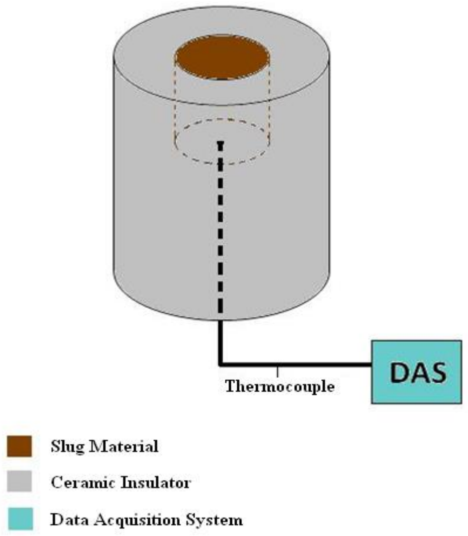

Figure 1 Schematic representation of Slug type Heat flux Gauge

The slug-type heat-flux sensor consists of a small cylindrical element called Slug, inserted into the face of the model but isolated from it, whereby it measures the heat flux. 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. [5]

Rate of rise of the slug temperature is proportional to the rate of heat transfer to the slug which can be mathematically expressed as

$$q = m\, C_p\, (dT/dt)\, A \qquad (1)$$

q – Heat Flux, W/m^2
A – Area of gauge, m^2
m – Mass of the slug, kg
C_p – Specific heat of the slug, J/kg-K
dT/dt – Rate of change of slug temperature, K/s

As per the second law of thermodynamics, no system can be 100% efficient and hence there will be some loss from the surface of the slug [13].

$$q = m\, C_p\, (dT/dt)\, A + L\, (T_s - T_a) \qquad (2)$$

L – Heat loss factor,
T_s – Slug Temperature, K
T_a – Ambient Temperature, K

Thermal Diffusivity is the ability of a substance to permit or undergo diffusion.

$$\alpha = K / \rho.C_p \qquad (3)$$

α – Thermal diffusivity(m^2/s)
K – Thermal conductivity (W/m^{2}K)
ρ – Density (kg/m^3)
C_p– specific heat of copper slug in (J/kg –K)

Response time for a thermocouple is inversely proportional to thermal conductivity. As the thermal conductivity increases the response time decreases.

$$t = 0.3\, L^2 / \alpha \qquad (4)$$

t – Response time (s)
L – Length of slug (l)
α – Thermal diffusivity(m^2/s)

E. Need for Slug Type Heat Flux Gauge

- Extremely useful in solving thermal problems under Transient conditions [6].
- Can be used as a diagnostic tool in the propulsion area, especially where the total test time is in the order of milliseconds and the heating rates are high.
- Useful where the size limitations do not allow the use of other sensors or when it is not feasible to provide cooling.
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II. PRELIMINARY DESIGN

A. Slug Design

Slug is the sensing element, it should have high thermal conductivity should withstand fatigue at high temperature. The slug is to be insulated by a thermal insulator on all but one surface which will be exposed to high temperature to measure heat flux. Copper is commonly used as a slug material in Heat flux gauge. But copper has a low melting temperature not suitable for high temperature applications. So the heat flux gauge having copper as slug material cannot be used for a temperature above 1100°C. Other materials have been explored.

Table 1
Materials with their Thermal Conductivity and Melting Temperature

Material	Thermal Conductivity (W/m-k)	Melting Temperature (°C)
Copper	400	1085
Silver	429	916.8
Tungsten	173	3422
Iridium	147	2477
Magnesium	156	650
Zinc	116	419.5
Steel	43	1370
Graphite	25-470	3000
Silicon Carbide	120	2730
Platinum	70	1768
Iron	80	1538

Graphite having thermal conductivity in range of 25-470 W/m-K) is available and it also has a high melting point of 3000°C [12]. Graphite was machined to a dimension of 3mm diameter and 3mm length. This had to be done so that the slug fits into the ceramic insulation.

As the temperature goes above 600°C, Graphite starts to undergo oxidation forming CO and CO_2 [7]. An inert atmosphere is required for higher temperatures which is not suitable for our applications. So Graphite slug was coated with a 40µ layer of Silicon Carbide [8]. This was done by a process known as Chemical Vapor Deposition (CVD). CVD is a chemical process used to produce high-purity, high-performance solid materials. In typical CVD, the substrate is exposed to one or more volatile precursors, which react and/or decompose on the substrate surface to produce the desired deposit.

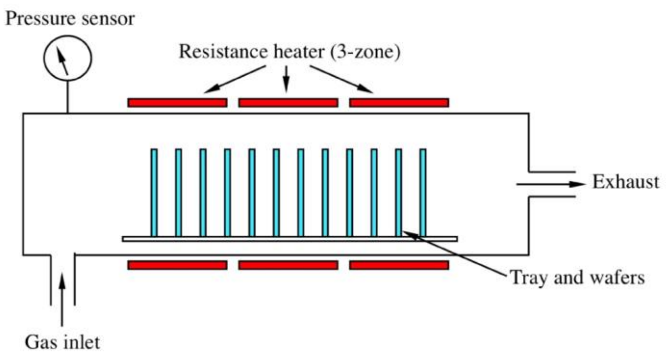

Figure 2 Chemical Vapor Deposition (CVD)

The substrate to be coated with silicon carbide is placed in a furnace which is heated by using sets of resistance coils. The substrate materials are arranged in a tray. They are coated with a precursor. The silicon carbide in vapour form is passed through the inlet of the furnace. It gets adsorbed on the surface of the substrate due to the precursor. At high temperature it reacts with the substrate on the surface and forms a coating. The standard thickness is 120 µm; however this can be modified within a range of 20 to 500 µm.

Characteristics of Silicon Carbide

- The silicon carbide layer has excellent oxidation resistance, corrosion resistance and chemical resistance.
- The silicon carbide layer is stable at high temperatures and is extremely hard.
- Prevents the parting and scattering of graphite particles, and the emission of gas and impurities from the graphite substrate.
- Both the graphite substrate and silicon carbide layer are of high purity.
- Both the graphite substrate and silicon carbide layer have a high thermal conductivity, and excellent heat distribution properties.
- Material is designed so that cracks and de-lamination do not occur.

Properties of Slug Material Used

- Density, $\rho = 1848$ kg/m^3
- Specific Heat at 300K, $C_p = 710$ J/ kg-K
- Thermal Conductivity at 300K, k = 104 W/m-K
- Thermal diffusivity, $\alpha = 75 \times 10^{-6}$ m^2/s
- Coefficient of thermal expansion = 4.3×10^{-6} /°C

Table 2
Variation of thermal conductivity and specific heat with temperature

Temperature(K)	Thermal Conductivity(W/mK)	Specific Heat (J/kg-K)
300	104	710.40
350	100.35	865.00
400	94.73	1025.80
450	90.42	1156.95
500	85.78	1268.6
550	81.6	1352.3
600	76.81	1423.5
650	73.25	1490.5
700	69.69	1549.2
800	66.13	1589.4
900	64.28	1645.4
1000	62.57	1683.1
1100	59.01	1712.4
1200	55.45	1737.5
1300	53.87	1762.6
1400	49.65	1808.7
1600	46.42	1854.7
1800	44.53	1925.9

From the above data curve fitting was done to obtain a 3rd degree polynomial equation which was fed into the computer to calculate heat flux.

B. Ceramic Insulation

For the 3mm Graphite Slug, the insulation is of 30mm diameter and 33mm length. A 3mm hole is made through the centre such that the 3mm Graphite slug along with the thermocouple can be inserted. The length of the insulator is taken as 10 times more than the slug length to reduce heat loss.

Properties of Ceramic Insulation

- Specific heat: 765 J/kg-K
- Thermal conductivity: 1.8 W/m-K
- Coefficient of thermal expansion: 8.1 x 10^{-6} /°C

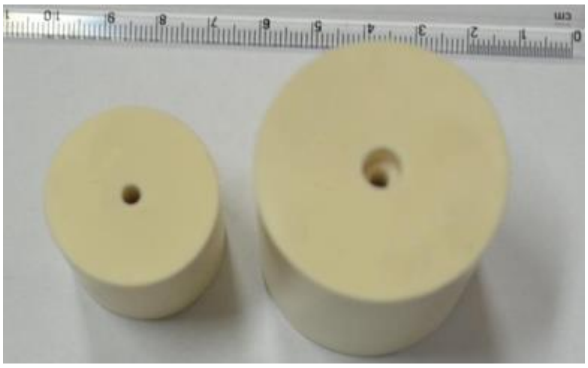

Figure 3 Ceramic Insulation

C. Thermocouple

The K- type thermocouple consists of two alloy wires, namely Chromel and Alumel which are covered by an aluminum sheath, which is a good conductor of heat [9]. So there can be heat loss when connected to graphite rod. To avoid this, the aluminum sheath of the thermocouple is removed and the Chromel - Alumel wires taken out. These wires are inserted into a 3mm ceramic tube, providing insulation and reducing heat loss.

D. Adhesive Cement

Adhesive cement is used to stick the slug material to the thermocouple wires. The same adhesive is also used in sticking the slug material to the ceramic insulation. The adhesive is made of 2 components, powder (Ceram Bond 571 – P) and liquid activator (Ceram Bond 571 – L). For the application 3 parts of powder and 2 parts of liquid (by weight) are mixed to form a thick paste. This paste is applied to the stick the graphite slug with the thermocouple and also to stick the Graphite – Thermocouple into the ceramic insulation to be air tight. This assemblage is dried for a minimum of 4 hours and then cured for 2 hours.

Properties of Adhesive Cement

- Specific Heat: 1.9 J/ kg-K - 2.2 J/ kg-K.
- Temperature Limit: 1760°C.
- Mix Ratio: Powder: Liquid :: 1.5: 1 (by weight)

E. Data Acquisition System (DAS)

Data Acquisition is the process of sampling signals that measure real world physical conditions and converting the resulting samples to digital numerical values that can be manipulated by a computer. The NI PXIe-1062Q chassis works with both PXI and PXI Express modules and can operate in a temperature range extended to 55 °C [10].

The National Instruments PXIe-1062Q 8-slot chassis is designed to meet the needs of a wide range of test and measurement applications, providing a high-bandwidth backplane to meet high-performance needs.

Figure 4 Screen shot of Data logging

F. Fabricated Heat Flux Gauge

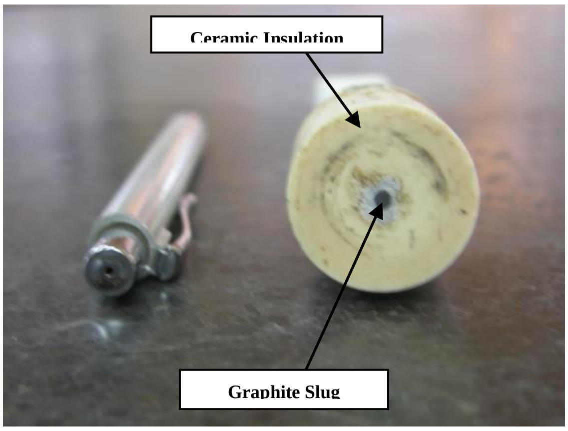

Figure 5 Side View Heat Flux Gauge

At the center of Heat Flux gauge a graphite slug is present which is attached to the Ceramic insulation using adhesive cement.

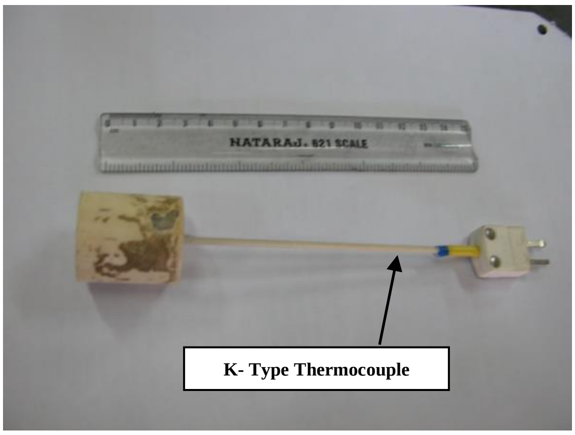

Figure 6 Top View Heat Flux gauge

A K-type thermocouple is attached to the back of the graphite slug. The thermocouple is placed inside a ceramic tube.

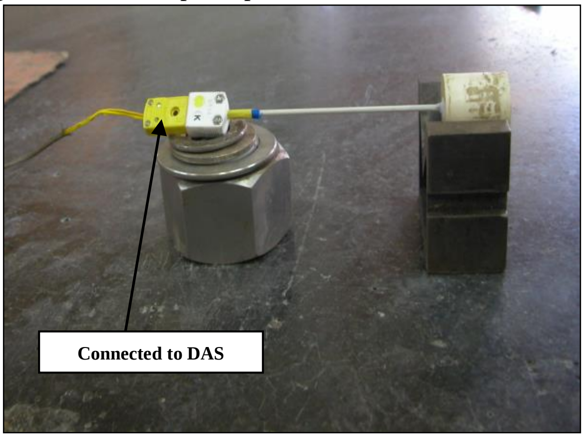

Figure 7 Graphite Heat Flux gauge connected to DAS

Using a connector the thermocouple is connected to Data Acquisition System.

III. EXPERIMENTS CONDUCTED

The Slug of the Heat Flux Gauge has to be heated using a heating source. For our experiments we have used 2 heating sources.

- Solder Rod (low temperatures)
- Oxy- Acetylene Flame (high temperatures)

In order to test the Heat Flux Gauge the following set of experiments were conducted.

A. *To test the Heat Flux gauges and to measure the heat flux produced using Solder Rod as heating source.*

The solder rod is switched on and it starts to get heated up. The gauge is set in position (slightly touching the solder rod) and DAS logging is started. The temperature of the gauge gradually starts to increase. The process is continued until a temperature of 500K is achieved. The gauge is moved back from the heating source and allowed to cool. The DAS is logged till this point.

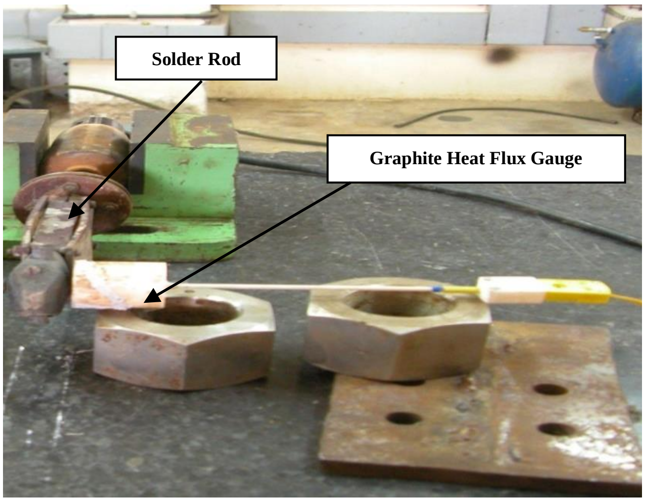

Figure 8 Graphite Heat flux gauge with solder rod as heating source

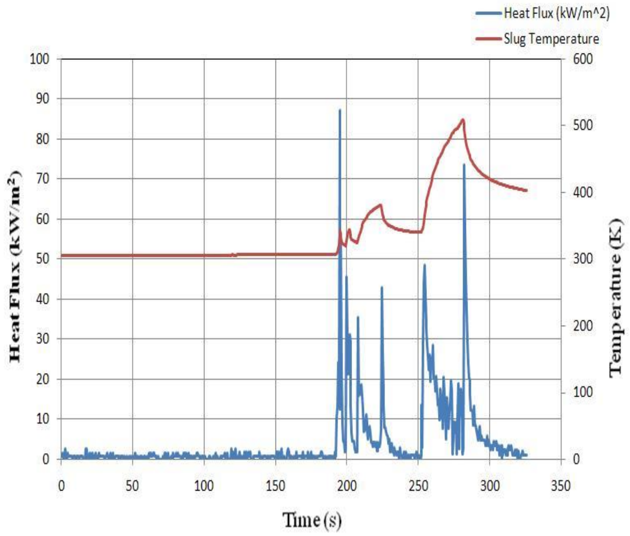

Figure 9 Temperature, Heat Flux vs. Time using solder rod as heating source

Inference from Graph

From the graphs it is inferred that as the difference in temperature increases, the heat flux increases, which is in accordance with formula. The sudden increase and decrease the heat flux values are due to variation in temperature. Maximum temperature was found to be 520 K and maximum heat flux obtained was around 87 W/m^2. At many points peaks were observed. These peaks were obtained due to transient conditions.

B. *Measure the Heat Flux produced using Oxy-Acetylene Flame as heating source.*

The torch is ignited and the flame is adjusted such that the medium flow rate is achieved. The gauge is set into position (slightly touching the flame) and DAS logging is started. The gauge is slowly moved into the flame such that its temperature increases gradually. The process is continued until a target temperature of 850 K is achieved. The gauge is moved back from the flame and allowed to cool. The DAS is logged till this point.

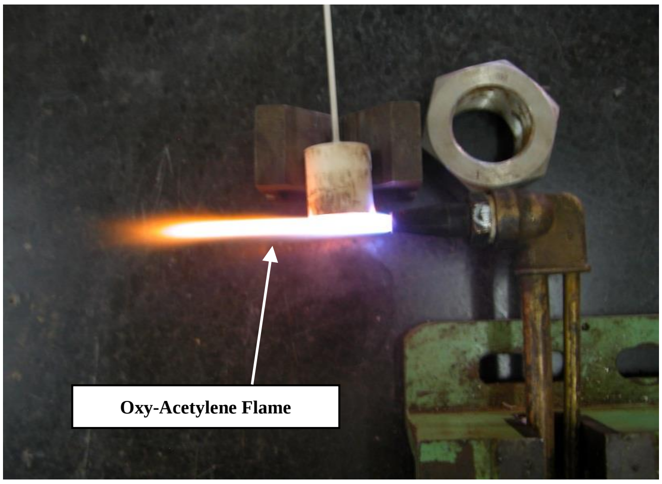

Figure 10 Graphite Heat Flux gauge with Oxy Acetylene flame as heating source

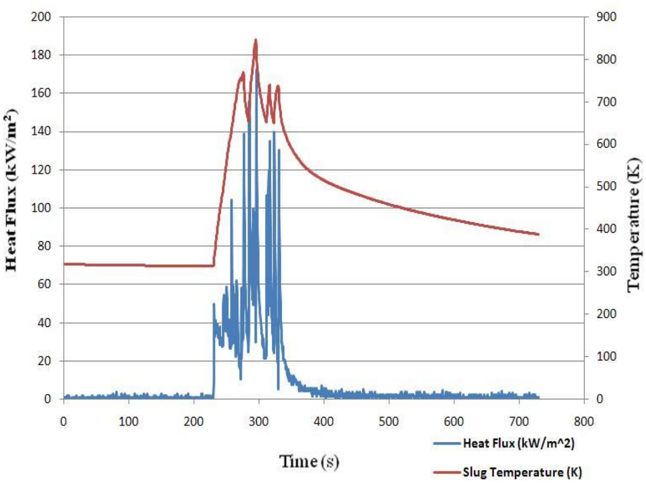

Figure 11 Temperature, Heat Flux vs. Time using Oxy Acetylene flame as heating source

Inference from Graph

Here, to expose the setup to a higher temperature we used oxy-Acetylene flame. Here maximum temperature attained was 850 K. Value of heat flux obtained here was 170 W/m^2 which is higher in comparison to solder rod experiment. Even here we can see peak points due to change in the value of dT/dt (Slope)

C. Comparison of Heat Flux produced using copper as slug material and graphite as slug material using Oxy-Acetylene Flame as heating source

The central axes of both the flame torch nozzle, Copper Slug and the Graphite slug are aligned perpendicular to each other. The graphite slug and copper slug are connected to the thermocouple. The Thermocouple end is connected to Data Acquisition System (DAS) and continuous data is logged. The torch is ignited and the flame is adjusted such that the medium flow rate is achieved. The gauges are set into position (slightly touching the flame) and DAS logging is started. Both the Copper Slug and the Graphite slug heat flux gauges are slowly moved into the flame such that its temperature increases gradually. The gauge is moved back from the flame and allowed to cool. The DAS is logged till this point.

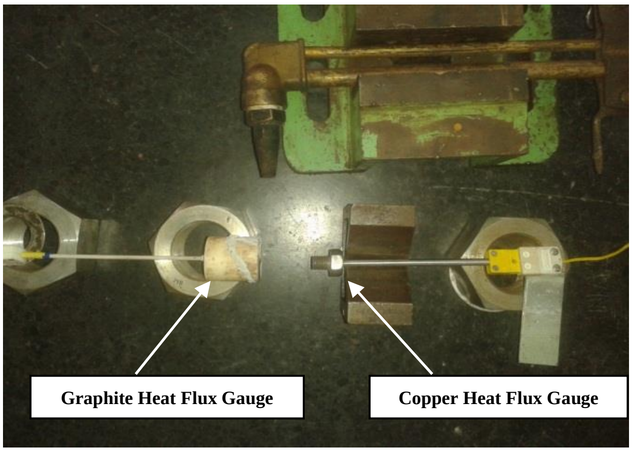

Figure 12 Heat Flux gauges with Copper and Graphite as Slug materials

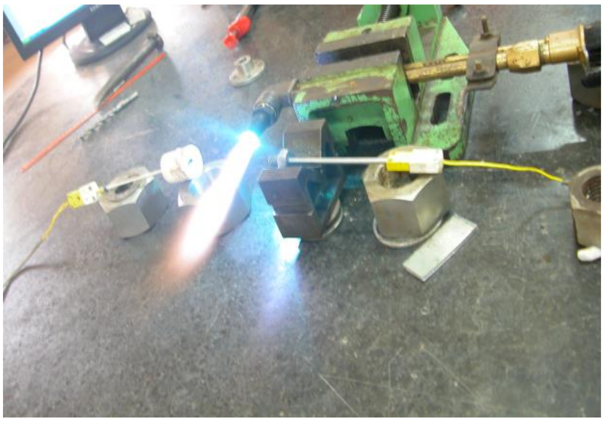

Figure 13 Heat Flux gauges with Copper and Graphite as Slug materials using Oxy- Acetylene flame as heating source

Copper can be considered as a reference gauge because of its high thermal conductivity and the values obtained using copper as slug material is in good agreement with actual values.

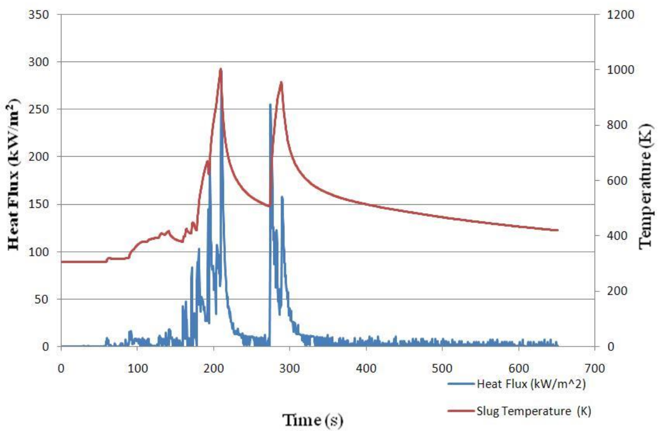

Figure 14 Temperature, Heat Flux vs. Time for Heat Flux gauge with Graphite as slug using Oxy- Acetylene flame as heating source

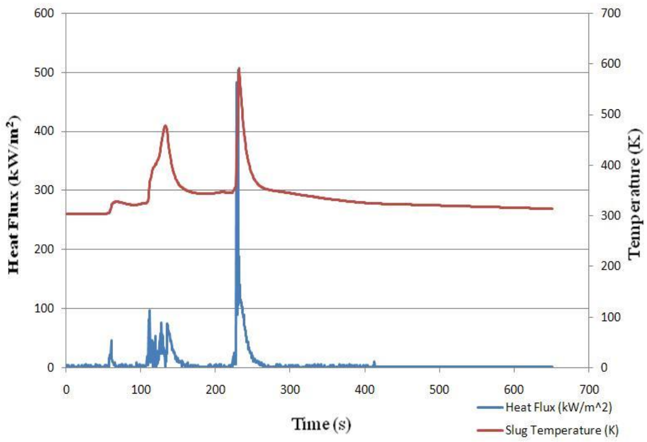

Figure 15 Temperature, Heat Flux vs. Time for Heat Flux gauge with Copper as slug using Oxy- Acetylene flame as heating source

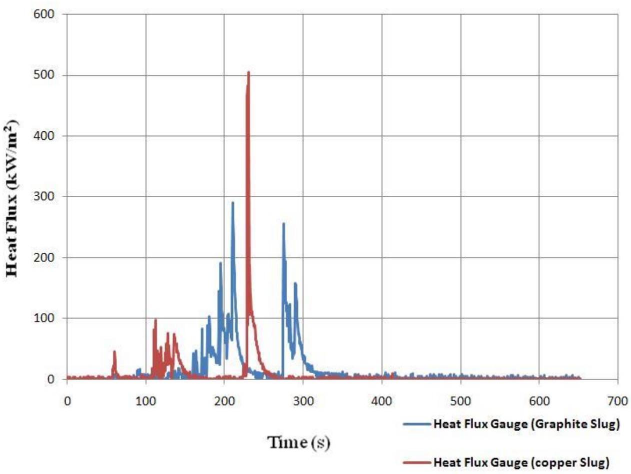

Figure 16 Comparison of Heat Flux produced with Copper and Graphite as Slug using Oxy-Acetylene Flame

Inference from Graphs

Thermal conductivity of Copper (393 W/ m-K) is higher than the thermal Conductivity of Graphite (100 W/ m-K). Response time for Copper Slug was found to be better compared to Graphite Slug. So, better heat flux measurement was made by Copper gauge.

To withstand higher temperature Graphite slug was used instead of Copper Slug. Graphite melting temperature is known to be 3000 K. To prevent oxidation above 873 K, Silicon Carbide (SiC) coating was done and was exposed to Oxy-Acetylene flame. Response time for Graphite gauge was more due to lesser thermal conductivity.

Thermal conductivity of Copper slug is very much higher compared to Graphite Slug. Hence the response time is less for Copper. Heat flux value measured by Copper Slug is considerably better (500 W/m^2). Heat flux value measured by Graphite Slug is less (295 W/m^2). But, Copper could not be used for higher temperature.

IV. CONCLUSION

Heat Flux vs. Time, Temperature vs. Time is obtained as shown in the previous graphs. It was clear from the previous graphs that slug material with higher thermal conductivity will yield better heat flux measurement. This is because as the thermal conductivity increases response time decreases, which is essential for any sensing element.

It is found that even at higher temperature Graphite has shown satisfying results. Graphite slug can yield sufficiently good measurements of varying high heat flux in the range of 75-300 kW/m^2.

SiC surface coating was successful in preventing oxidation of Graphite at high testing temperatures. Hence Graphite slug can be used to measure heat flux at high temperature conditions with SiC coating.

The graphite which was used in experiments had low thermal conductivity (104 W/m-K), so by using graphite material of higher thermal conductivity, better results can be obtained. Heat flux gauge can be calibrated to obtain more accurate results [11].

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