International Journal of Mechanical Engineering Research.
ISSN 2249-0019 Volume 12, Number 1 (2022), pp. 1-15

http://www.ripublication.com

Estimation of Heat Flux Using Inverse Heat Conduction Method

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Abstract

Heat flux is defined as the rate of heat transfer per unit area from or to the surface. The S.I unit of heat flux is W/m2. It is a vector quantity that gives information about the direction of heat flow in a system whereas temperature is a property of a substance at a given point. Heat flux can be measured with the help of devices like gardon gauge, slug calorimeter, and thin film gauge etc. The outer skin temperature is measured with the help of thermocouples. In addition, outer surface temperature is measured by using a thermal imaging camera. Thermal imaging camera gives the temperature value based on the sensed infrared radiation emitted from the research combustor. The outer skin temperature value can be used in steady state heat conduction method to determine the heat flux. The method of estimating heat flux and temperature on an inaccessible surface by measuring the temperature on an accessible boundary is known as inverse heat conduction method. A project was carried out in order to determine the heat flux. The project work deals with the estimation of heat flux within the duct of a SGTE (Small Gas Turbine Engine) nozzle test rig.

Keywords: Heat flux, thermal imaging camera, infrared radiation, inaccessible surface, inverse heat conduction method.

1. INTRODUCTION

Inverse heat conduction is defined as the method, which is used to determine heat flux and temperatures on an inaccessible surface of a wall by measuring the temperature on an accessible boundary. Inverse analysis can also be used in the estimation of thermo-physical properties of the shield during operating conditions at such high temperatures. In many heat transfer situations, the surface heat flux and temperature histories must be determined from transient temperature measurements at one or more interior locations. This is an inverse problem. The concept of an inverse problem has gained widespread acceptance in modern applied mathematics, although it is unlikely that any rigorous formal definition of this concept exists. Most commonly, by inverse problem is meant a problem of determining various quantitative characteristics of a medium such as density, thermal conductivity, surface loading, shape of a solid body etc by observation over physical fields in the medium. Temperature sensors are placed beneath the hot surface of the shield and the surface temperature is recovered by inverse analysis.

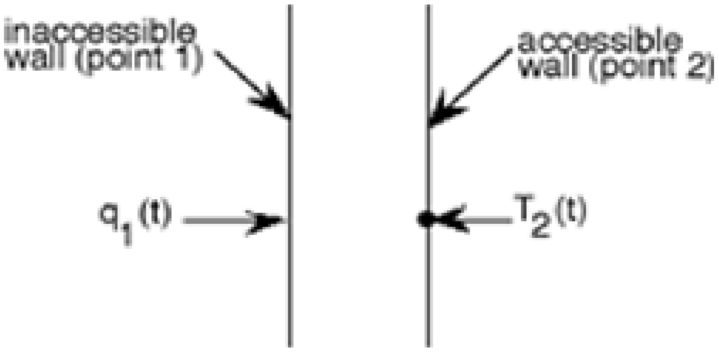

Fig 1: Principle of inverse heat method

1.1 Thermocouple

A thermocouple is an electrical device consisting of two dissimilar conductors forming electrical junctions at differing temperatures. A thermocouple produces a temperature-dependent voltage as a result of the thermoelectric effect, and this voltage can be interpreted to measure temperature. Thermocouples are a widely used type of temperature sensor. Thermocouple works on the principle of Seebeck effect. Seebeck effect states that, “When two dissimilar metals are connected together to form a junction and maintained at two different temperatures, an emf is induced in it”. This emf is known as thermo-electric emf. Commercial thermocouples are inexpensive, interchangeable, are supplied with standard connectors, and can measure a wide range of temperatures.

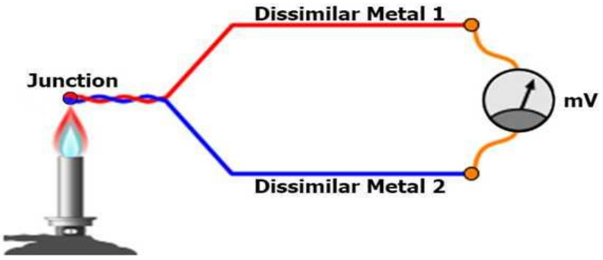

Fig 2: Principle of thermocouple

Thermocouples are widely used in science and industry. Applications of thermocouple include temperature measurement for kilns, gas turbine exhaust, diesel engines, and other industrial processes. Thermocouples are also used in homes, offices and businesses as the temperature sensors in thermostats. They also as flame sensors in safety devices for gas-powered major appliances. Thermocouples are also suitable for measuring over a large temperature range, from −270 up to 3000 °C.

Formula used for calculating temperature

$$\Delta V = S\Delta T$$

where,

ΔV = Change in voltage in volts

S = Seebeck coefficient in volts per Kelvin

ΔT = Change in temperature in Kelvin.

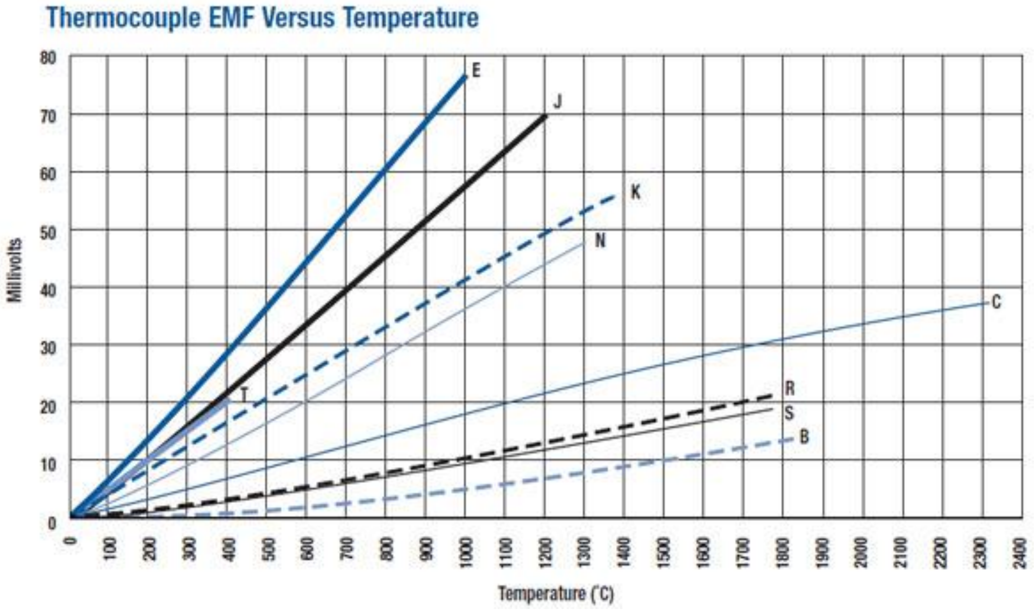

Fig 3: Temperature vs voltage graph

K Type thermocouple is used in the project due to the following reasons

- Inexpensive, accurate, reliable.
- Well suited for oxidizing atmosphere.
- High temperature resistance up to 1250°C.
- It has good radiation hardness.

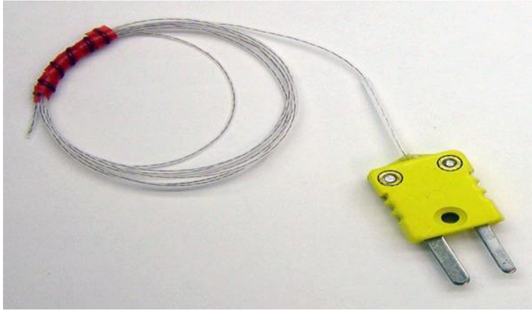

Fig 4: K Type thermocouple

1.2 THERMAL IMAGING CAMERA

A thermal imaging camera is a device that uses infrared radiation to form an image, similar to a common camera that forms an image using visible light. Instead of the 400–700 nm range of the visible light camera, infrared cameras operate in wavelengths as long as 14,000 nm (14 µm). These infrared rays were used mainly for thermal measurement.

THEORY OF OPERATION

Infrared energy is just one part of the electromagnetic spectrum, which encompasses

radiation from gamma rays, x-rays, ultra violet, a thin region of visible light, infrared, terahertz waves, microwaves, and radio waves. These are all related and differentiated in the length of their wave (wavelength). All objects emit a certain amount of black body radiation as a function of their temperatures. A special camera can detect this radiation in a way similar to the way an ordinary camera detects visible light. It works even in total darkness because ambient light level does not matter.

Fig 5: Thermal imaging camera

INITIAL ADJUSTMENTS FOR THE OPERATION OF THERMAL CAMERA

CAMERA FOCUS

Some infrared cameras are manufactured with a fixed focus lens. Focusing these images requires skill to find the best “sweet spot” distance from your target which provides the clarity of detail in the image that you require. For infrared cameras with manual focusing capability, the onus is on you to take your time tightly focusing your target to lock in the clearest focused image when you capture the picture. The more sophisticated infrared cameras have either an auto-focus or a push button auto-focus feature. Both of these options provide good focusing of the camera but also require diligence on your part as they are not as consistent as your hand-eye coordination of a manual focus. Focus is one of the keys to successful thermographers.

CHANGING THE EMISSIVITY SETTING OF THE CAMERA

Emissivity is the amount of radiation emitted from an object compared to that of a perfect emitter of radiation when both are at the same temperature. A lower emissivity setting would be used for highly reflected objects and a high emissivity setting would be used for low reflective objects. Objects that are non-metal or that have a rougher surface will have a higher emissivity. Adjusting the emissivity is important when taking temperature measurements or when comparing two different objects' temperatures. Incorrect emissivity settings will make objects appear hotter or colder then what they really are. Not all infrared cameras will allow the user to adjust the emissivity of the imager. Lower cost IR cameras may be locked into a default emissivity for wood or drywall.

ADJUSTING THE CAMERA FOR REFLECTED TEMPERATURE

The reflective temperature setting allows you to compensate for temperatures from surrounding objects reflecting on your target object. If reflected thermal energy from surrounding objects is suspected, move the camera around in the area of the target and see if the hot or cold spot moves with the camera. If it does, it is a reflection from another object, if it does not, it is a true hot or cold spot. In order to find out what the reflective temperature is, you will need to adjust the emissivity of the camera to 1.0, then place a piece of crinkled aluminum foil on a piece of cardboard. Place the foil between the camera and the object you intend to view and note the temperature of the foil. Then input the temperature of the foil into the reflective temperature setting for your infrared camera. Just like emissivity, reflective temperature is important when taking temperature measurements or comparing temperatures of two or more objects.

THERMAL TUNING

Thermal Tuning of your infrared camera involves adjusting the span or temperature range that the camera sees while in manual viewing mode.

Infrared cameras today usually have an automatic viewing mode and a manual viewing mode. When the imager is in automatic mode, the camera will automatically adjust the temperature scale to what is being viewed which causes the display to change colors frequently when the camera is moved from place to place. Manual mode allows you to adjust the span to a desired range. Then the camera will always display this temperature range or span until you switch back to automatic mode.

APPLICATIONS OF THERMAL IMAGING CAMERA

- Industrial applications

Thermal imaging cameras for industrial applications are powerful and non-invasive tools for monitoring and diagnosing the condition of electrical and mechanical installations and component.

- Flare detection

During certain production processes gasses are generated which are burned off in flares. The flames generated can be invisible to the human eye. It is important to be sure that the flare is burning. Otherwise, harmful gasses might enter the atmosphere. Thermal imaging can easily see if the flare is burning or not.

- Tank level detection

Thermal imaging can also easily be used for tank-level detection. Emissivity effects or to temperature differences the thermal image clearly shows the level of the liquid.

- Medical Applications

Thermograph is non invasive, non contact equipment that uses the heat from a body to aid in making diagnoses of a number of healthcare conditions. It is completely safe and uses no radiation. Although operating in real time, the imagers are able to store many images which can be retrieved for subsequent analysis. Imagers are in use in hospitals, medical centres, surgeries and by individual practitioners including physiotherapists.

The main categories of current applications are:

- Breast pathology

The use of the thermal imager as a screening tool in the detection of breast cancer is proving to be a powerful tool in the battle against cancer and other diseases.

- Musculoskeletal problems

Thermal Imaging can be used to diagnose a variety of disorders associated with neck, back and the limbs.

Applications of Thermal Imaging in Agriculture

Thermal imaging has a potential application in many operations involved in agriculture, starting from assessing the seedling viability, estimating soil water status, estimating crop water stress, scheduling irrigation, determining disease and pathogen affected plants, estimating fruit yield and evaluating maturity of fruits and vegetables.

2. EXPERIMENTAL SETUP

The experiment for the heat flux measurement was conducted in the Test Rig 1, HSCTF, Propulsion Division. The objective of this test is to estimate the heat flux due to high temperature gas flow. The thermocouple is placed at the top surface of the nozzle duct. And this thermocouple end is connected with the computer, then the accurate readings are observed.

The equipments used in the test rig are as follows:

- Gate Valve.
- Pressure Regulator.
- Orifice Plate.
- Pre - Heater.
- Settling Chamber.
- Nozzle.

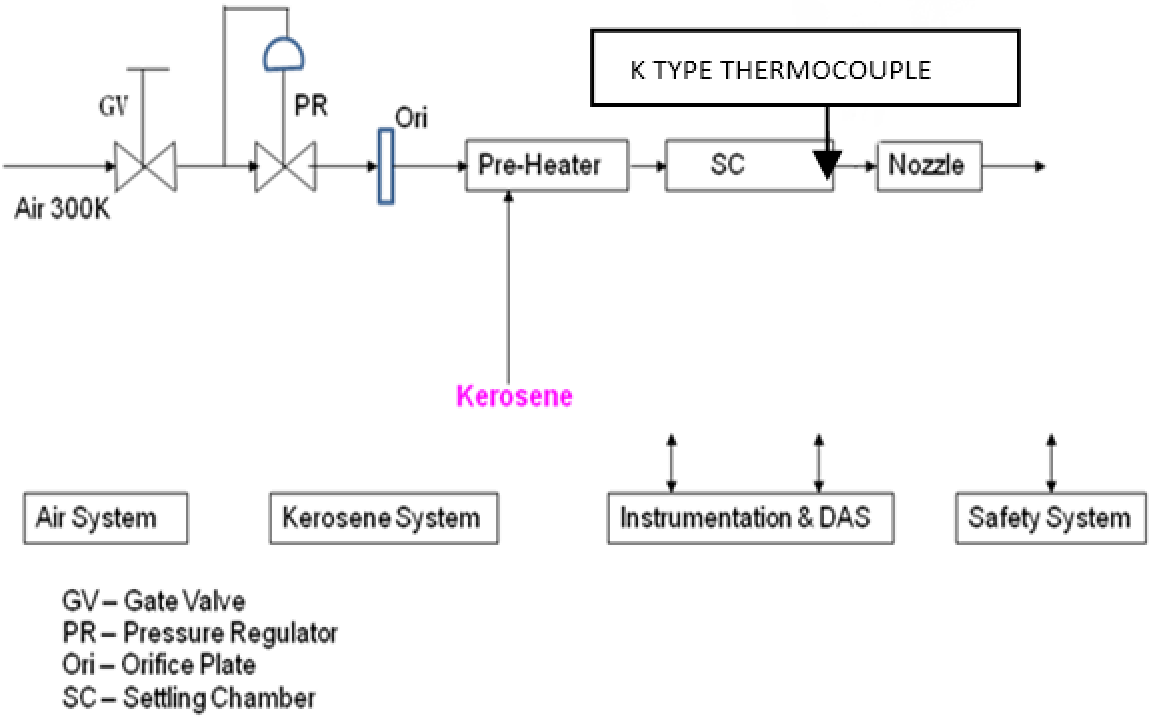

Fig 6: Schematic diagram of the test rig

Working

- Initially pressurized air from the compressor is fed into the Test rig 1.
- The pressure regulator regulates the flow of compressed air into the system.
- Once the required mass flow rate is obtained, the fuel pump is switched ‘ON’.
- The fuel is burnt inside the pre-heater and made to flow through the system at required temperature.
- This hot mixture from pre-heater gets settled in the settling chamber.
- This burnt gases is passed through the nozzle.
- This nozzle produces the necessary thrust.

Fig 7: Picture of test rig with Thermal Imaging Camera

FORMULAS AND CALCULATION

- Estimation of heat transfer coefficient for free convection

Surface temperature, $T_w = 413.6125$ K,

Ambient temperature, $T_\infty = 306$ K

Film temperature, $T_f = (T_w + T_\infty)/2 = 87$ °C

The following are the properties of the fluid taken from the data book,

Density of fluid, $\rho = 0.9804$ Kg / m3

Kinematic viscosity, $\upsilon = 21.797 \times 10^{-6}$ m2/s

Prandtl number, Pr = 0.6906

Thermal conductivity, k = 0.031037 W/mK

Coefficient of thermal expansion, $\beta = 1/T_f = 0.00277 K^{-1}$

The formula to calculate the Grashof number is taken from the data book under free convection.

Grashof number, Gr = gßL3ΔT/υ2= $3.93\text{x}10^8$

Gr*Pr = $2.72\text{x } 10^8 < 10^9$

The above multiplied value can be used to find whether the flow is laminar or turbulent. In our case, the flow is laminar since GrPr value is less than 10^9. Then the corresponding Nusselt number formula taken from the data book is given by,

Nusselt number, Nu = 0.59 x (Gr*Pr)0.25 = 75.77

Using the general definition of the Nusselt number, we can calculate the value of heat transfer coefficient due to free convection.

Nu = hL / k

Length, L = 0.4m

Therefore, Heat transfer coefficient for free convection, h=10 W/ m^2k

- Estimation of heat transfer coefficient for forced convection

Reynolds number, Re = $4m_{total} / \pi D\mu$

Where, m_{total} = mass flow rate = 1.0149 6 kg/s

At 901 k, from data book

Absolute viscosity, $\mu = 46.68\text{x}10^{-6}$ Ns/m2

k = 0.07629 W/mK; Pr = 0.717

Then the corresponding Nusselt number formula taken from the data book is given by,

Thus Nu =$0.023 \, Re^{0.8} \, Pr^{0.4}$

Nu = 297.412

Nu = h D / k

where, D = 0.17m; r1 = 0.085m; r2 = 0.09m

Therefore, heat transfer coefficient for forced convection, h = 133.46 W/m^2K

- Resistance due to forced convection [R1]

R1 = (1/2 п L) x (1/ h r1) = $3.5 \text{ x } 10^{-2}$ K/W

- Resistance due to conduction from inner to outer wall [R2]

Thermal conductivity of the material, k (plain carbon steel) = 43.3 W/mK

R2 = (1/2 п L) x [(1/k) ln (r2/ r1)] = $5.2 \text{ x } 10^{-4}$ K/W

- Resistance due to free convection [R3]

R3 = (1/2 п L) x (1/ h r2) = 0.4420 K/W

Heat transfer, Q = ΔT / R

where, $\Delta T = T_g - T_\infty$

$R = R1 + R2 + R3$

Therefore, heat transfer, $Q = 12.45$ KW

Heat Flux, $q = Q / A = 5.601$ KW / m^2

Estimation of inner wall temperature [T_{wi}]

$Q = (T_g - T_{wi}) / R1$

Thus, the inner wall temperature, $T_{wi} = 465.25$ K

RESULTS AND DISCUSSIONS

The data acquired from the DAS is directly recorded in a spreadsheet file by “LABVIEW”. This spreadsheet contains valuable data about various parameters like Heat flux (q), Gas temperature (Tgas), Skin temperature (Tskin), Mass flow rate (mg), Total pressure (Po) with respect to time. These data were plotted against time and the trend is discussed and analyzed to understand the change in various parameters due to transient heat transfer. The experiment was performed in two trails and the graphs were plotted between various parameters as follows:

TRIAL 1

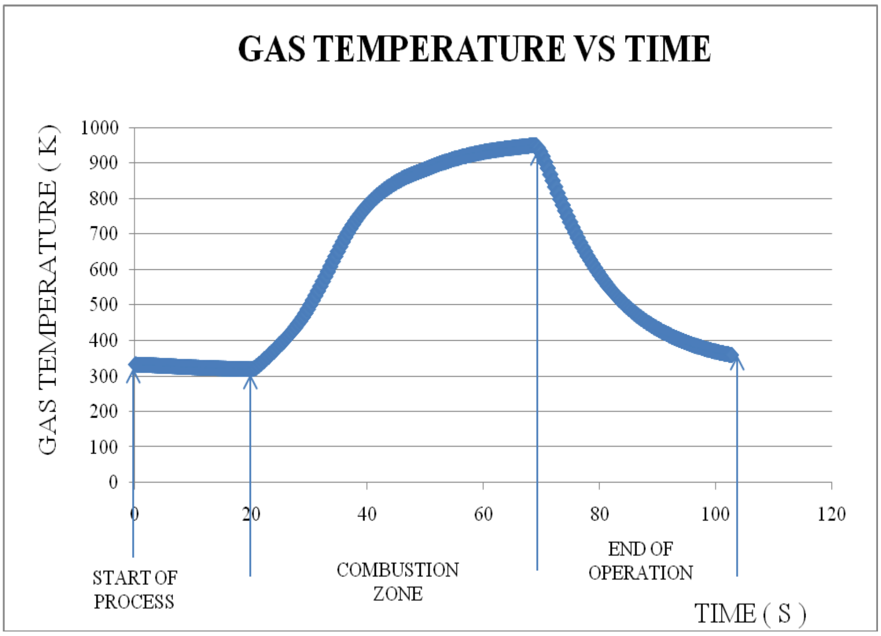

Fig 8: Gas temperature vs Time

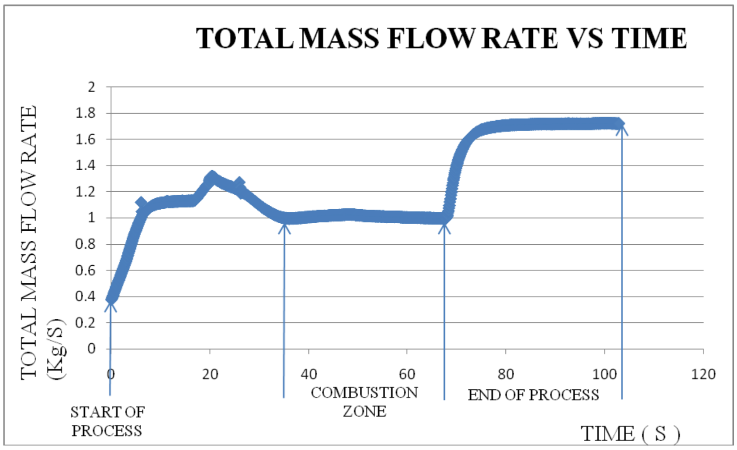

Fig 9: Mass flow rate vs Time

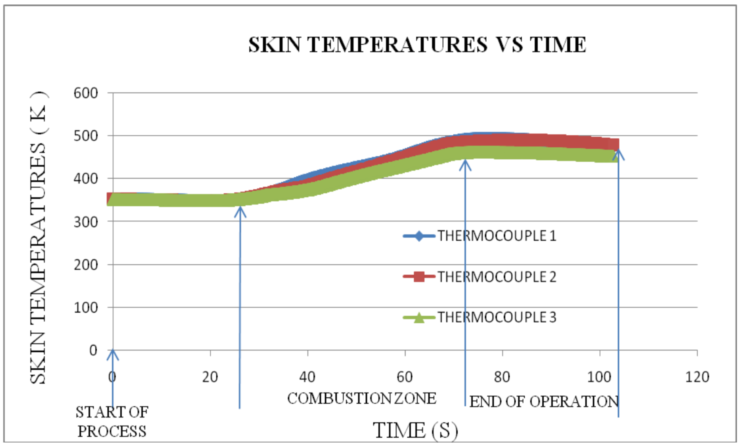

Fig 10: Skin temperature vs Time

TRIAL 2

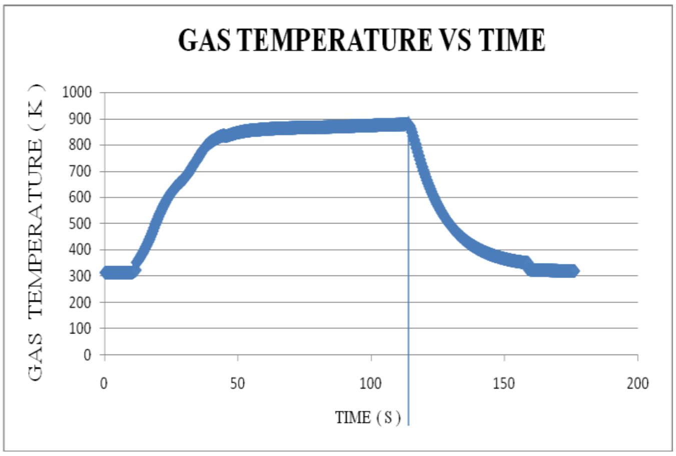

Fig 11: Gas temperature vs Time

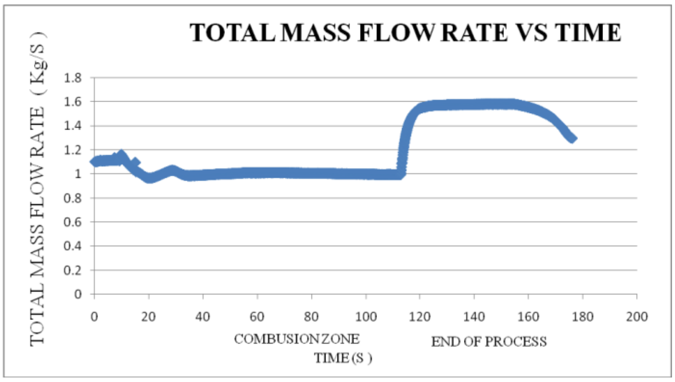

Fig 12: Mass flow rate vs Time

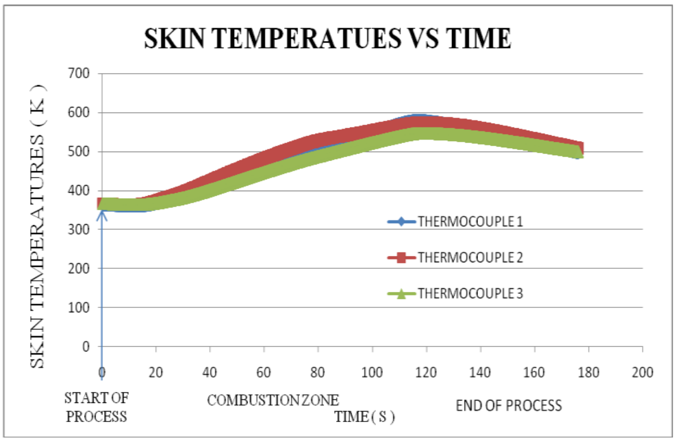

Fig 13: Skin temperature vs Time

From the above graph, we can observe that the gas temperature remains constant up to 20 s and then gradually increases to reach a maximum temperature of 950K at t=70 s due to the combustion that takes place in the pre-heater. Then the temperature falls as the combustion ceases and the gas is made to settle in a settling chamber. We can see that the mass flow rate increases with respect to time and tends to remain constant for a short period of time and then suddenly increases due to blockage in the electro-pneumatic valve of the fuel.

If we take a look at the skin temperatures, we can understand that the skin temperature of the duct rises as the time progresses. This shows that the heated gas is responsible for the increase in skin temperature. The graph in trail 2 also follows the same conditions as discussed in the above-mentioned points.

THERMAL CAMERA TEMPERATURE VS TIME

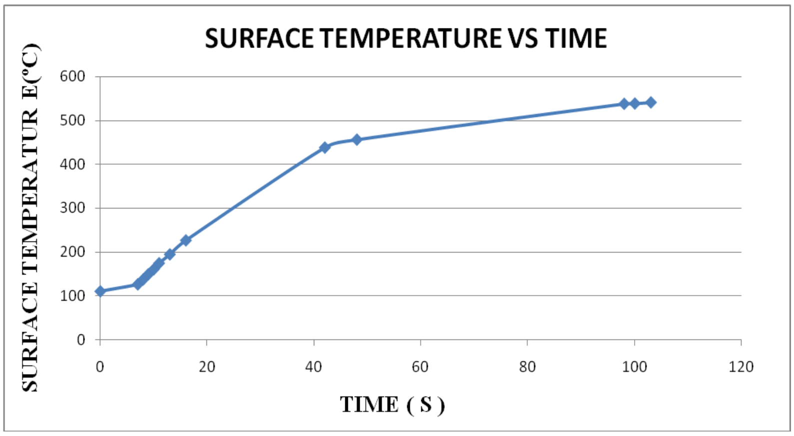

Fig 14: Surface temperature (thermal camera) vs Time

From the above graph, the surface temperature of the duct increases as the time increases. When the surface temperature of the duct measured with the help of thermal camera is compared with that of the surface temperature recorded from the thermocouple , we came to know that the thermal camera reads ahead of thermocouple by 169°C

which may be due to the following reasons:

- Emissivity dependence of the thermal camera
- Calibration of thermal camera
- Distance of the thermal camera from the test rig
- Ambient temperature conditions.

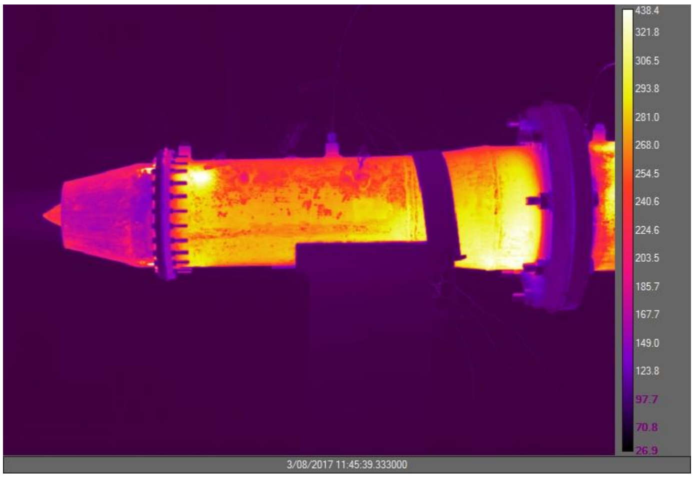

Fig 15: Thermal Image of Test Rig

3. CONCLUSIONS

Heat flux measurement plays an important role in thermal systems. The objective of the project which is to estimate the heat flux within the inner surface of the duct of a subsonic test rig has been successfully carried out. The experiment was carried out in the subsonic test rig with provided inlet conditions such as gas temperature, mass flow rate, Mach number and pressure.

During the experiment, outer surface temperature of the duct was found with the help of K-type thermocouple. The estimated heat flux value after the experiment was found to be 5.601 KW/m2.

The project also deals with the measurement of outer surface temperature of the duct using thermal imaging camera. The temperature error between thermocouples and the thermal imaging camera was also found.

ACKNOWLEDGEMENT

We would like to express our sincere thanks to Dr. KS BABAI, the Secretary of Meenakshi Sundararajan Engineering College, Dr. K Balasubramanian, HOD of Mechanical department, Meenakshi Sundararajan Engineering College Mr. M. Vadivel, Assistant Professor, Meenakshi Sundararajan Engineering College for their guidance and support in completing this journal.

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