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Measurement of thermal radiative heat transfer using a multi-axis heat flux sensor

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Abstract. Heat transfer always occurs in human life and can be perceived its benefits and losses. The heat transfer is divided into three according to transfers media, namely conduction, convection, and radiation. One example of cases where there are three processes of heat transfer is when there is a fire in a room. During a fire, the heat from the fire will travel into the surrounding environment and affect the objects around it with radiation, conduction, and convection. Heat that travels through radiation certainly does not require a medium of delivery because the heat is traveled in the form of electromagnetic waves and can travel to a very long distance. Distance, view factor, and placement of an object will affect the amount of radiation to be received from the heat of fire. Therefore, to examine the effect of distance, the viewing factor and the placement of objects against radiation, writer designs a multi-axis heat flux sensor. Instrument with multi-axis heat flux sensors or by the name of a Multi-Axis Radiometer will be designed which will then be tested to determine the results of the design. Instrument called Multi-Axis because the workbench of the instrument can be rotated 90°. Testing of the apparatus will include the heating temperature, the distance of the sensor to the heater, the sensor offset to the heater, the viewing angle of the sensor to the heater, and the orientation of the workbench. The results of testing distance and offset are validated by the theoretical calculations.

1. Introduction

The case where thermal radiation occurs is in the event of a fire in the room. In the event of fire, heat from fire will be transferred to the environment by conduction, convection, and radiation. Heat transfer in fires is an important factor in flame development, firespread, and fire suppression[1]. If the heat transfer in a fire is uncontrolled, it could make the fire become bigger and wider. When the heat of fire hit on a material surface by radiation, then there are three properties, some will be reflected, some will be absorbed, and some will be transmitted. The closer the distance to the object by the source of fire, then intensity of radiation will be greater. So that every object in the room has the same risk in the fire even if not directly exposed by fire[2].

In order to withstand the heat transfer and its effects is needed the appliance that can show the values from the effects of thermal radiation. The instrument is used to measure values is the Heat Flux Sensor. The Heat Flux Sensor will be mounted on a device called Radiometer. In this research, the use of radiometer is useful to measure the heat that is received by an object and the effect on the distance



and the angle of view of the heat source. In addition to measuring heat from thermal radiation, the heat from thermal convection can also be measured with this instrument. The tests are performed to obtain data. Then, data will be compared with the result of the theoretical thermal radiation heat flux calculations as a reference for testing this instrument.

2. Theory

2.1. Radiation

Radiation is the transfer of energy through electromagnetic waves that can move through the empty space, or objects and transparent fluid[3]. The heat flux of radiation that is received a point is defined as the following

$$\dot{q}'' = \varphi \varepsilon_e \sigma T_e^4 \quad (2.1)$$

Where the q'' is the radiant heat flux (W/m²), φ is the configuration factor, ε_e is emissivity from the surface of the transmitter, σ is Stefan-Boltzmann constant (5.67×10^{-8} W/m²K⁴), and T_e is the absolute temperature from the surface of the transmitter radiation (K).

When radiation emitted by a surface and accepted by a surface, the calculation of the heat flux becomes

$$\dot{q}'' = \varphi \varepsilon \sigma (T_e^4 - T_r^4) \quad (2.2)$$

View factor or configuration factor is the value of how much radiation transmitter will be seen by the recipient surface.

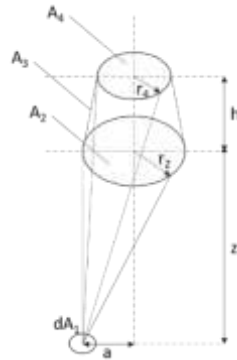


Figure 1. Radiation from one surface to another Surface.

From the picture above, from the position of dA_1 , view factor is represented with equation F_{d1-3} ,

$$F_{d1-3} = F_{d1-2} - F_{d1-4} \quad (2.3)$$

View factor F_{d1-3} represent the fraction of radiation energy that leave the surface of the specimen dA_1 to every direction until it reaches the area 3. View factor for the exchange between dA_1 and the area 2 can be shown by the following equations.

$$F_{d1-2} = \frac{1}{2} \left(1 - \frac{1 + H_2^2 - R_2^2}{\sqrt{Z_2^2 - 4R_2^2}} \right) \quad (2.4)$$

where $H_2 = z/a$, $R_2 = r_2/a$ and $Z_2 = 1 + H_2^2 + R_2^2$. The exception on the common (2.4) occurs when dA_1 is located on the center line, where $a = 0$ then,

$$F_{d1-2} = \frac{r_2^2}{z^2 + r_2^2} \quad (2.5)$$

Equation (2.2) also applies for F_{d1-4} so F_{d1-3} can be written to

$$F_{d1-3} = \frac{1}{2} \left[\left(1 - \frac{1+H_2^2-R_2^2}{\sqrt{Z_2^2-4R_2^2}} \right) - \left(1 - \frac{1+H_4^2-R_4^2}{\sqrt{Z_4^2-4R_4^2}} \right) \right] \quad (2.6)$$

And for $a = 0$,

$$F_{d1-3} = \frac{r_2^2}{z^2+r_2^2} - \frac{r_4^2}{(z+h)^2+r_4^2} \quad (2.7)$$

where $H_4 = (h+z)/a$, $R_4 = r_4/a$, and $Z_4 = 1 + H_4^2 + R_4^2$.

Equation (2.7) will be substituted into the heat flux equation (2.1) become,

$$q'' = F_{d1-3} \varepsilon \sigma T^4 \quad (2.8)$$

where T is the value of the average temperature from heating element[4].

2.2. Convection

In free convection fluid motion is due to buoyancy forces within the fluid, while in forced convection it is externally imposed. Buoyancy is due to the combined presence of a fluid density gradient and a body force that is proportional to density. In practice, the body force is usually gravitational but there also several ways in which a mass density gradient may arise in a fluid, but for the most common situation it is due to the presence of a temperature gradient [3]. In this research, the heater will be assumed as vertical plate and mostly buoyancy forces induce a free convection boundary layer in which the heated fluid rises vertically as shown below.

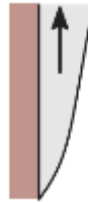


Figure 2. Free convection boundary layer on a vertical plate [3].

2.3. Radiometer

The Radiometer has thus schematic diagram as the figure 3 is a configuration to get the value of the heat radiation energy. The heat energy received by the detector will be related to the Stefan-Boltzmann constant with the view factor

$$R = \sigma F (T_s^4 - T_a^4) \quad (2.9)$$

Then,

$$F = \frac{R}{\sigma (T_s^4 - T_a^4)} = \frac{R}{q_b} \quad (2.10)$$

View factor (F) will relate to the view factor (θ) from the heat source and the view factor can be stated in

$$F = \sin^2 \theta \quad (2.11)$$

So,

$$R = \sin^2 \theta \times \sigma \times (T_s^4 - T_a^4) = \sin^2 \theta q_b \quad (2.12)$$

Point of view (θ) can be different depends on the distance Radiometer (x) to a heat source such as figure 3.

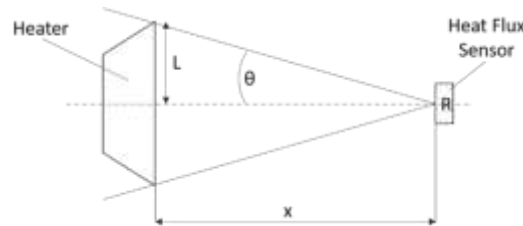


Figure 3. Schematic Point of View on Heat Sources.

P-355etoint of view (θ) can be defined to

$$\theta = \tan^{-1} L/X \quad (2.13)$$

where L is half of the length from surface of the heat source when it is square and the radius of the surface of the heat source when a circle[5].

The sensor used on the Radiometer is a thermal sensor to measure the heat flux. This sensor is usually called a heat flux sensor. This heat flux sensor uses the working principle of Gardon and Schmidt Boelter or have a working principle same as seebeck effect. The sensor is equipped with a black absorbent that is useful for capturing radiation. Inside the heat flux sensor there is a main sensor called thermopile. The thermopile will measure the temperature difference read on the front and back of the heat flux sensor[6]. The received temperature value will be converted to voltage so that it can be transmitted via cable and received in data collector.



Figure 4. Heat Flux Sensor[6].

Heat Flux (W/m^2) is obtained by the result of the voltage (U) produced divided by its sensitivity (S)

$$\phi = U/S \quad (2.14)$$

The sensitivity value is printed on the specification of the sensor. However, when the sensor temperature is below 10°C , then

$$\phi = \frac{U}{S} + \sigma(T + 273,15)^4 \quad (2.15)$$

Where σ is Stefan-Boltzmann Constant ($5,67 \times 10^{-8} \text{ W/m}^2\text{K}^4$).

3. Methodology

Radiometer that will be used for this research equipped with Conical Heater as heat source and will be done by several methods, such as heating temperature, sensors' distance to heater, sensors' offset to center point of heater, sensors' point of view to heater, and orientation of workbench. Each test is performed in 1 minute when the temperature read on the control system is stable and constant. In this test, the data will be read and collected through LabView 2016 and Microsoft Excel 2016 software. There will be at least three parameters of experiment, i.e. temperature of heat source, sensors' distance, and sensors' offset to center point of heat source. All of three parameters have many combinations for experiment. The results of experiment become experiment data of heat flux value from sensor readout. Furthermore, experiment data will be compared to radiative heat flux theoretical calculation in order to find the error value of the experiment data.

4. Results and discussion

4.1. Effect of sensors' distance

Testing the sensor distance from the heater at a distance of 10 cm, 20 cm, 30 cm, and 40 cm from the heater. The offset and point of view on this test is set at 0 cm and 0° with a flat work desk orientation. The control temperature used is 312.46 °C[7]. The data obtained from the test results are plotted so that the graph in figure 5. From the graphic results can be proved that the distance affects the amount of heat flux received by an object.

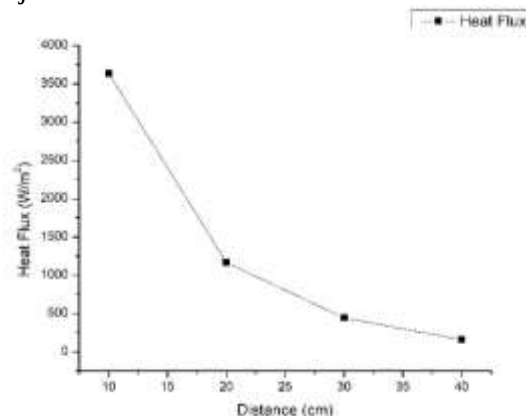


Figure 5. Distance vs Heat Flux Graph[8].

4.2. Effect of heating temperature and sensors' distance

Testing for variations in temperature and distance of sensor include all variations of the heating temperature and the sensor distance from the heater. The heating temperature are conducted at 273.74°C, 291.47°C, 312.46 °C, 331.16°C, and 351.11°C. For the sensors' distance are same as previous experiment explanation. The position of the offset and the sensor point of view on the heater in this test is 0 cm and 0° with the orientation of the flat work table. From the graph that has been plotted, it appears that the heat flux will increase with increasing temperature and the closer the sensor distance to the heater. At a distance of 10 cm from the heater, the heating flux value dominated and reads linearly with increasing temperature. While at a distance of 20 cm, 30 cm, and 40 cm is not completely linear because at the temperature control 330 °C to 350 °C increase heat flux is read only slightly. This can be caused by the distance of the sensor from the heater so that there is distraction from the environment. This distraction can occur because the Radiometer tool is not given a special cover. However, with the linear trend of graphs it can be proven that the distance and temperature affect each other from the magnitude of the heat flux.

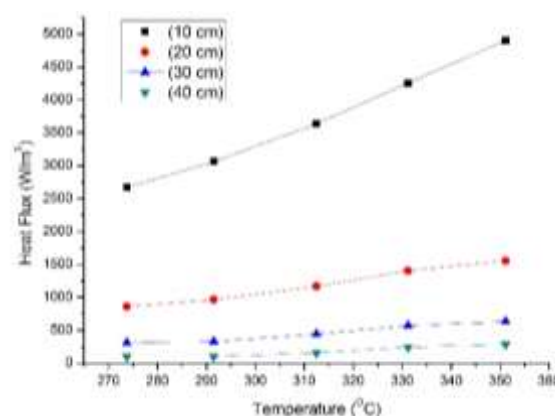


Figure 6. Temperature vs Heat Flux Graph[8].

4.3. Effect of offset and sensors' distance from heater

Variations are combined with the sensor distance from the heater to see the comparison between the distances. The offsets tested were -7 cm, -3.5 cm, 0 cm, 3.5 cm, and 7 cm. The negative value indicates that the sensor is on the left side of the heater and the positive value indicates the sensor is on the right of the heater. 7 cm is chosen as the largest offset value because the diameter of the heater is 16 cm so that the outer surface side of the heater is 7 cm. Distance variation in the test is all the distance variations, ie 10 cm, 20 cm, 30 cm, and 40 cm. The temperature used is 312.46°C with the sensor point of view 0° and the orientation of the flat work table. The graph of the test results is shown in figure 7.

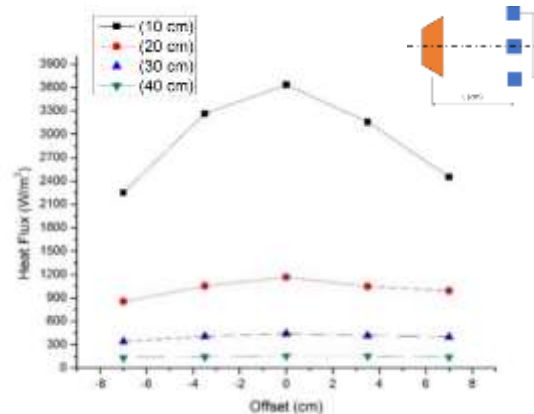


Figure 7. Sensors' Offset vs Heat Flux Graph[8].

4.4. Sensors' distance error

Theoretical calculation is done to compare and measure the error value of the experiment data. Theoretical calculation is done by equation (2.12) and T value are 273,74 °C, 291,47 °C, 312,46 °C, 331,16 °C, and 351,11 °C. When the T value of 273,74 °C, the error value at 10 cm is 48,54%, at 20 cm is 35,35%, at 30 cm is 1,58% which become the lowest overall error value, and at 40 cm is 42,99%. Then the T value is increased to 291,47 °C, the error value at 10 cm is 48,2%, at 20 cm is 32,12%, at 30 cm is 6,35%, and at 40 cm is 50,51%. After that, when the T value of 312,46 °C, the error value at 10 cm is 50,2%, at 20 cm is 36,5%, at 30 cm is 7,63%, and at 40 cm is 34,06%. Until T value 312,46 °C, the lowest error value still at distance of 30 cm. When the T value of 331,46 °C, the error value at 10 cm is 53,67 %, at 20 cm is 43,54 %, at 30 cm is 21,16 %, and at 40 cm is 11,4 %. Lastly, when the T value reach the highest temp on experiment of 351,11 °C the error value at 10 cm is 54,23 %, at 20 cm is 38,53 %, at 30 cm is 17,16 %, and at 40 cm is 8,76 %. The last two T value show that the lowest error value exists at distance of 40 cm.

4. Conclusions

The present work has allowed us to get to the following conclusions:

1. Radiative heat flux starts to dominate when the distance of sensor at 30 cm. In this case is proven by small error value which is the result of comparison between experiment data and radiative heat flux theoretical calculation data.
2. At the distance of 10 cm, there is assumption that convective heat flux is read by sensor. Big error value from experiment data and radiative heat flux theoretical calculation data shown if there could be an indicator to determine the deviation that occurs is a convective heat flux. Also, the convective boundary layer could be covered the area where the distance of sensor is 10 cm and make the data read by sensor includes convective heat flux.
3. Heating temperature is linear to heat flux. Hotter temperature of heat source makes the heat flux that is read by sensor also bigger.

4. Configuration factor will affect the amount of heat flux which is received. In this experiment configuration factor is represented by distance of sensor to heat source. Further sensor from heat source make the heat flux that is read smaller.

5. Acknowledgement

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