Experiment # 12. RADIATION HEAT TRANSFER CHARACTERISTICS

12.0 Objectives
The objectives of this experiment are to
1. Verify experimentally the relation between thermal radiation intensity and temperature. (Stefan Boltzmann’s law)
2. Investigate the effect of radiation shape factor on the radiation heat exchange between surfaces
3. Verify the effect of surface properties on radiation heat transfer

12.1 Unit Description

- The unit comprises a rigid track (1) onto which are fitted three carriages and together with a heat source, light source, instruments and accessories that allow the various properties of heat and light radiation to be investigated. The track has a graduated scale (5) so that the distances between components may be measured.

- Carriage (4) is designed to support a combination of metal plates (11) with different surface finishes (polished, matt black, dull grey) and each having a duplex surface temperature measuring thermocouple attached. T7 to T10 are duplicated for easy connection to the Hilton Data Logger and are terminated with 2-way edge connectors. These are not utilized without the optional HC111A Data Acquisition Upgrade.

- A transverse carriage will support cork coated variable aperture plates C1(21) and plastic light filter plates C1(20).

- Carriage (2) is designed to support either a radiometer (12) for heat transfer experiments or a light meter (23) for light related experiments. The radiometer signal is displayed on a dedicated console and the light meter is a handheld LCD meter. Both signals may be retransmitted to the data logger.

- The radiometer is supplied with a reflective shield that fits in the front aperture to minimize heating of the detector body by the heat source when the device is not in use.

- Radiation from external sources (sunshine or room heaters, particularly radiant devices) should be minimized where possible.

- At the left end of the carriage may be located a heat source (10) and at the right end a light source (16).

- The heat source (10) consists of a 200W ceramic heater and 100mm diameter black aluminum plate which is heated by a variable voltage (240v max) electrical supply through connector (7). The exposed face of the plate is coated with a heat resistant matt black paint with an emissivity close to 1.0.
LAWS OF RADIANT HEAT TRANSFER & RADIANT HEAT EXCHANGE

Figure C1
Figure 2: Experimental setup

Figure 3: Schematic Diagram of the heating unit and accessories
The surface temperature of the plate is measured by duplex thermocouple T10, the thermocouple is fitted with a plug (8) for direct connection to the Heat Transfer Service unit H111, the heater is rated to produce approximately 200 Watts at 230 V AC. The plate can reach in excess of 300°C when operated at maximum voltage.

12.2 Operating Procedure

Refer to Figures 1, 2 and 3

1. Ensure that the H111 main switch is in the off position (the three digital displays should not be illuminated). Ensure that the residual current circuit breaker 2(V) on the rear panel is in the ON position.

2. Turn the voltage controller anti-clockwise to set the AC voltage to minimum.

3. Connect the power lead (7) to the 8-way socket 2(S) on the front panel. Connect the thermocouple plug (8) to thermometer socket T10 on the heat transfer service unit H111. Note the schematic arrangements shown on Figure 3.

4. Fit the radiometer to the sensor carriage (13). Note the schematic arrangements shown on Figure 3.

5. Position the W/m² display console on top of the H111 console. Connect the power cable between the console and plug the radiometer signal cable into the front panel.

6. Install the plates (11), (19,20), (21,22) in the left hand carriage (4) if required, as specified in the experimental procedure. Note the schematic arrangements shown in Figure 3.

7. Turn on the H111 main switch and the three digital displays should illuminate. The radiometer display should also illuminate. The required temperature is displayed on the LED digital display by turning the rotary selector switch.

8. Auto-Zero the radiometer by pressing the right hand * button twice.

9. Rotate the voltage controller clockwise to increase the voltage to that specified in the procedure for each experiment.

10. Allow the system to reach stability, and take readings and make adjustments as instructed in the individual procedures for each experiment.

11. When the experimental procedure is completed, it is good practice to turn off the power to the heater by reducing the AC voltage to zero and then turn off the H111 main switch. Allow the components to cool before storing them away safely.

12.3 CAUTION

During operation the heated plate will be operating at approximately 250 to 300°C. Treat the unit with caution and observe operating procedures as there is a severe burn hazard.
12.4 Experiment 12a: To show that the intensity of radiation varies as the fourth power of the source temperature (To demonstrate the Stefan-Boltzmann Law.)

12.4.1 Experiment Steps

1. Follow the basic operating procedures given in Section 12.2. Install the heated plate (10) at the left hand side of the track and install the radiometer (12) on the right hand carriage (2). No items are installed in the left hand carriage for this experiment but one of the black plates should be placed on the bench and connected to thermocouple socket T9.

Schematically this produces a system as shown below.

![Diagram of experiment setup](image)

2. Ensure that the radiation shield is in position in the radiometer aperture and station the radiometer in the 900mm position as shown above.

3. The radiometer should be left for several minutes after handling with the radiation shield in position to ensure that residual heating has dissipated.

4. Follow the Operating procedure in section 12.2 up to point ‘7, but do not increase the supply voltage to the heater from the zero condition.

5. Monitor the W/m² digital display and after several minutes, the display should reach a minimum. Finally, ‘Auto-Zero’ the radiometer by pressing the right hand * button twice.

6. Leave the radiation shield in position and rotate the voltage controller clockwise to increase the voltage to 40 Volts, Select the T10 position on the temperature selector switch and monitor the T10 temperature.

7. When the T10 temperature has reached a maximum condition, remove the radiation shield (The small black plastic cover of the radiometer) without touching the radiometer and move the radiometer to a position 300mm front the heated plate. Immediately the indicated value should start to rise. Monitor the digital display until the displayed value reaches a maximum and then record the following.
8. Again, without touching the radiometer, move the carriage holding the radiometer to a point 900 mm from the heated plate and replace the radiation shield.

9. Increase the heater voltage by 40 volts and again monitor T10 until a maximum is reached.

10. Without touching the radiometer, remove the radiation shield and move the radiometer to a position 300 mm from the heated plate. Immediately the indicated value should start to rise.

11. Monitor the digital display until the displayed value reaches a maximum and then record the following.

\[ \text{T9. T10, x (300 mm in this case), R.} \]

12. Keep repeating the above procedure until the heater voltage is set to 240 volts (or maximum available). Note that after each adjustment, the radiometer heat shield should be replaced and the radiometer moved away from the heated plate to prevent heating of the radiometer body.

### 12.4.2 Theory

The Stefan Boltzmann law states that for a black body

\[ q_b = \sigma (T_s^4 - T_a^4) \]  \hspace{1cm} (12.1)

Where

- \( q_b \): Energy emitted per unit area of blackbody radiator, W/m².
- \( \sigma \): Stefan Boltzmann constant = \(5.67 \times 10^{-8} \) W/m² K⁴
- \( T_s \): Absolute temperature of the radiator, K
- \( T_a \): Absolute temperature of the surroundings, K

This is the energy emitted from the surface.

At a distance, \( x \), from the surface, the energy received (and indicated) by a detector R will be related to the Stefan Boltzmann constant by a factor F such that

\[ R = \sigma F (T_s^4 - T_a^4) \]  \hspace{1cm} (12.2)

Hence,

\[ F = \frac{R}{\sigma (T_s^4 - T_a^4)} = \frac{R}{q_b} \]  \hspace{1cm} (12.3)
12.4.3 Tables of observations and calculations

Table 12-1: Data collection for Stefan Boltzmann experiment

<table>
<thead>
<tr>
<th>T9</th>
<th>T10</th>
<th>x</th>
<th>R</th>
<th>R_c</th>
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Table 12-2 Calculated Data

<table>
<thead>
<tr>
<th>T_s</th>
<th>T_a</th>
<th>q_b</th>
<th>R_c</th>
<th>F  = R_c/q_b</th>
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12.4.4 Sample calculation

1. Using the values of T_a and T_s for every reading, convert them first to absolute temperature (K)
2. Calculate q_b using equation 12.1
3. For this unit, C = 0.786, calculate the corrected R, R_c = C * R
4. Calculate F, F = q_b/R_c

Does the factor F change? What do you conclude?
12.5 Experiment 12b: To show that the intensity of radiation measured by the radiometer is directly related to the radiation emitted from a source by the view factor between the radiometer and the source.

12.5.1 Experiment Steps

1. Follow the basic operating procedure in section 12.2. No items are installed in the left hand carriage for this experiment but one of the black plates should be placed on the bench and connected to thermocouple socket T7.

2. Schematically this produces a system as shown in Figure 3.

3. Ensure that the radiation shield is in position in the radiometer aperture and station the radiometer in the 900 mm position as shown above.

4. The radiometer should be left for several minutes after handling with the radiation shield in position to ensure that residual heating has dissipated.

5. Follow the Operating procedure on section 12.2 up to point 7, but do not increase the supply voltage to the heater from the zero condition.

6. Monitor the W/m² digital display and after several minutes, the display should reach a minimum. Finally, ‘Autozero’ the radiometer by pressing the right hand * button twice.

7. Leave the radiation shield in position and rotate the voltage controller clockwise to increase the voltage to maximum volts. Select the T10 position on the temperature selector switch and monitor the T10 temperature.

8. When the T10 temperature has reached a maximum condition, remove the radiation shield (without touching the radiometer). Immediately the indicated value should start to rise. Monitor the digital display until the displayed value reaches a maximum and then record the following.

   T9, T10, x (900mm in this case), R.

9. Again without touching the radiometer, move the carriage holding the radiometer to a point 800mm from the heated plate. Again, the radiometer reading will start to rise. Allow this to reach a maximum and repeat the observation

   T9, T10, x (800 mm in this case), R.

10. Repeat the above procedure in reducing steps of 100 mm until the radiometer is 200 mm from the heated plate.

11. Note that at a distance of less than 200 mm, the heated plate completely fills the field of view of the radiometer and accuracy of measurement reduces.
12.5.2 Theory
Refer to the Stefan Boltzmann law states for a black body given in equation (12.1). This is the energy emitted from the surface. At a distance x from the surface, the energy received (and indicated) by detector R is related to the Stefan Boltzmann constant by a factor F (Refer to equation 12.2)

The view factor, F, is related to the view angle $\theta$ such that

$$F = \sin^2 \theta$$  \hspace{1cm} (12.4)

Therefore,

$$R = \sin^2 \theta \times \sigma \times \left( T_s^4 - T_a^4 \right) = \sin^2 \theta \times q_b$$ \hspace{1cm} (12.5)

12.5.3 Tables of observations and calculations

Observations

Table 12-3 Observations of the view factor experiment

<table>
<thead>
<tr>
<th>$T_9$</th>
<th>$T_{10}$</th>
<th>$x$</th>
<th>$R$</th>
<th>$R_c$</th>
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### Table 12-4 Calculated data, view factor experiment

<table>
<thead>
<tr>
<th>$T_s$</th>
<th>$T_a$</th>
<th>$q_b$</th>
<th>$\theta$</th>
<th>$\text{Sine}^2\theta$</th>
<th>$q_b \times \text{Sine}^2\theta$</th>
<th>$R_c$</th>
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<tbody>
<tr>
<td>K</td>
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12.5.4 Sample calculations, For every reading

1. Convert temperatures ($T_s$, $T_a$) to absolute values (K).
2. Calculate $q_b$ using equation 12.1.
3. Calculate $\theta$, $\theta = \tan^{-1} \left( \frac{50}{x} \right)$ radians
4. Calculate $\text{Sine}^2\theta$.
5. calculate $q_b \times \text{Sine}^2\theta$
6. Calculate $R_c$
7. Compare the last two columns
12.6 Experiment 12c: To determine the emissivity of radiating surfaces with different finishes, namely polished and grey (silver anodized) compared with matt black.

12.6.1 Experiment Steps

1. Follow the basic operating procedure in section 12.2. Install the heated plate (10) at the left hand side of the track and install the radiometer (12) on the right hand carriage (2).

   **Note:**
   For the following experiment, the results are more graphic if all of the plates can be made to reach a similar temperature during heating. For this reason it is beneficial if the back faces (the face facing the heated plate) of the grey and polished plates are soot blackened with a candle. Both sides of the black plate, however, may be soot blackened.

2. Position the plate holder (4) with the left hand slot 50 mm from the heated plate. Install one of the blackened plates (11) in the left hand slot of the plate holder (close to the heated plate).

3. Connect the thermocouple plug of the blackened plate to the T7 socket on the Heat Transfer Service Unit H111.

4. Connect the thermocouple of the grey (anodized aluminum) plate to the socket market T8 on the front of the service unit and place the plate on the bench adjacent to the unit where it can record the ambient temperature.

5. Connect the thermocouple of the polished plate to the socket market T9 on the front of the service unit and place the plate on the bench adjacent to the unit where it can record the ambient temperature.

   Schematically this produces a system as shown below.

![Figure 5: Schematic of experiment 12c](image)

6. Ensure that the radiation shield is in position in the radiometer aperture and station the
radiometer in the 900mm position as shown above.

7. The radiometer should be left for several minutes after handling with the radiation shield in position to ensure that residual heating has dissipated.

8. Follow the Operating procedure in section 12.2 up to point 7, but do not increase the supply voltage to the heater from the zero condition.

9. Monitor the W/m² digital display and after several minutes, the display should teach a minimum. Finally ‘Auto-Zero’ the radiometer by pressing the right hand * button twice.

10. Leave the radiation shield in position and rotate the voltage controller clockwise to increase the voltage to maximum volts. Select the T7 position on the temperature selector switch and monitor the T7 temperature.

11. When the T7 temperature has reached a maximum condition, remove the radiation shield (without touching the radiometer) and move the radiometer carriage to a point 200 mm from the black plate. Immediately the indicated value should start to rise. Monitor the digital display until the displayed value reaches a maximum and then record the following.

  T7 (black plate), T8 (the ambient temperature) and R

12. Replace the radiation shield in the radiometer and without touching the radiometer move the carriage back to the 900 mm position.

13. With care remove the black plate and replace with the grey (anodized aluminum) plate. Select the T8 position on the temperature selector switch and monitor the T8 temperature.

14. When the T8 temperature has reached a maximum condition, remove the radiation shield (without touching the radiometer) and move the radiometer carriage to a point 200 mm from the grey plate.

15. Immediately the indicated value should start to rise. Monitor the digital display until the displayed value reaches a maximum and then record the following.

  T8 (grey plate), T9 (the ambient temperature) and R.

16. Repeat the entire procedure using the polished plate and record.

  T9 (polished plate), T7 or T8 (either plate may be used for ambient temperature) and R.

12.6.2 THEORY

The Stefan Boltzmann law can be expanded such that for a grey body radiator

\[ q_g = \varepsilon \sigma (T_s^4 - T_a^4) \]  

(12.6)

Where \( \varepsilon \) is the emissivity of the radiating surface and for a black body \( \varepsilon = 1.0 \). For a grey body, however, \( \varepsilon < 1.0 \)
In experiment 12b, it was demonstrated that at a distance $x$ from the radiator, the incident radiation $R$ falling on a detector can be determined from

$$ R = F \sigma \left( T_i^4 - T_a^4 \right) $$

(12.2)

Where $F$ is a view factor,

This may also be expanded for a grey body such that

$$ R = \varepsilon F \sigma \left( T_i^4 - T_a^4 \right) $$

(12.7)

For a non circular black plate the relationship $F = \sin^2 \theta$ cannot be applied.

However, the actual view factor may be determined through experiment if one of the shapes is assumed to be a black body radiator $\varepsilon = 1.0$

Under these conditions the radiation $R$ falling on the detector at a distance $x$ is

$$ R = F \sigma \left( T_i^4 - T_a^4 \right) $$

Hence

$$ F = \frac{R}{\varepsilon \sigma \left( T_i^4 - T_a^4 \right)} = \frac{R}{q_h} $$

(12.8)

If $F$ can be determined and assuming that the distance $x$ is not altered then for the non black plates

$$ R = \varepsilon F \sigma \left( T_i^4 - T_a^4 \right) $$

Hence

$$ \varepsilon = \frac{R}{F \sigma \left( T_i^4 - T_a^4 \right)} = \frac{R}{F q_h} $$

(12.9)


12.6.3 Observations and Calculations

Table 12-5 Observation for surface properties experiment

<table>
<thead>
<tr>
<th>Sample #</th>
<th>T7 Black plate</th>
<th>T8 Grey plate</th>
<th>T9 Polished plate</th>
<th>R</th>
<th>Re</th>
<th>X</th>
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<tbody>
<tr>
<td></td>
<td>°C</td>
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Table 12-6 Results of surface properties experiment

<table>
<thead>
<tr>
<th>Plate</th>
<th>Units</th>
<th>Black plate</th>
<th>Grey plate</th>
<th>Polished plate</th>
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</thead>
<tbody>
<tr>
<td>Tₛ</td>
<td>K</td>
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<tr>
<td>Tₐ</td>
<td>K</td>
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<td>qᵦ</td>
<td>W/m²</td>
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<td>Rₑ</td>
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12.6.4 Detailed Calculations, C = 0.786

Consider one of the plates (say, black)

1. Convert temperatures (Tₛ, Tₐ) to absolute values (K).
2. Calculate qᵦ using equation 12.1.
3. Calculate Rₑ = R * C
4. Use equation 12.8 to calculate F

Now consider the grey plate

5. Convert temperatures (Tₛ, Tₐ) to absolute values (K).
6. Calculate Rₑ = R * C
7. Use equation 12.9 to calculate ε.

Repeat this procedure for polished plate.

Report the results in both observations and calculations tables in addition to the discussion of your results, figures and conclusions in a technical report that should also include an appropriate abstract, conduction and list of references.