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ESE – 40… ENERGY SYSTEMS LABORATORY -…
Heat Radiation Experiment Report

Student No :
Name-Surname :
Experiment Date :
Grade :

2.3 Heat Radiation Experiment

2.3.1 Objective

The purpose of this experiment is to understand thermal radiation which is one of the heat transfer mechanism. Also, substantial terms concerning with thermal radiation such as emissivity, view factor, and radiation intensity will be perceived through the experiments performed.

2.3.2 Introduction

Thermal radiation has a different characteristic in comparison to conduction and convection in that it does not need any medium. To illustrate, heat transfer between a hot object and a vacuum chamber to which the hot object is placed cannot be occur with conduction or convection due to lack of medium. However, thermal radiation will be responsible for the amount of heat transfer between the object and vacuum chamber. Energy transfer with radiation is transported by electromagnetic waves which travel at the speed of light in a vacuum. From this aspect, energy transfer with radiation is the fastest heat transfer mechanism.

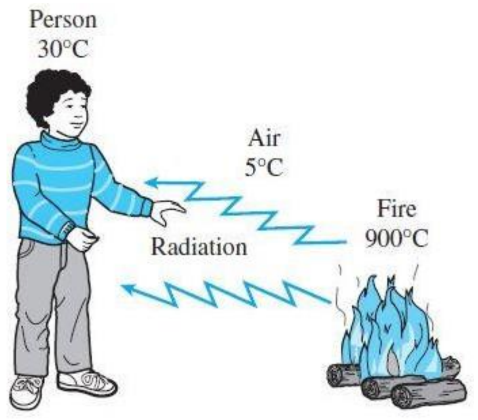

Figure 2.5.1. Heat transfer by radiation when medium is colder than both bodies

The most important example for radiative heat transfer is that the energy of the sun reaches the earth through radiation. Furthermore, we have the knowledge that heat transfer by conduction and convection occurs in the direction of decreasing temperature. The mechanism for the radiative heat transfer is a bit different in that thermal radiation can occur even if temperature of medium is lower than those of two bodies between which energy is transferred as demonstrated in Figure 2.5.1. Thermal radiation emission increases with increasing temperature and all matter with a temperature above absolute zero emits thermal radiation.

2.3.3 Theory

2.5.3.1 Blackbody radiation

Even if their temperatures are the same, different bodies may emit different amounts of radiation per unit surface area. A body that emits maximum radiation is called blackbody.

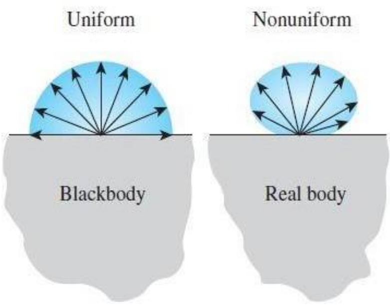

Figure 2.5.2. Radiation emission from blackbody and real surface

A blackbody is defined as a perfect emitter and absorber of radiation. At a specified temperature and wavelength no surface can emit more energy than a blackbody. A blackbody absorbs all coming radiation from other bodies. Besides, as illustrated in Figure 2.5.2, a blackbody emits radiation energy uniformly in all directions unlike real bodies. Therefore, a blackbody is a diffuse emitter which is the term used for emission independence of direction. The radiation energy emitted by a blackbody per unit time and per unit surface is expressed by Equation 2.5.1;

$$E_b = \sigma T^4 \tag{2.5.1}$$

where E_b is the blackbody emissive power, $\sigma = 5.67 \cdot 10^{-8}$ W/(m^2·K^4) is the Stefan-Boltzmann constant and T is the temperature of the surface in terms of Kelvin.

2.5.3.2 Radiation intensity

The radiation is emitted by all parts of a plane surface in all directions and the directional distribution of emitted surface is not uniform if the object is not a blackbody. Therefore, a quantity should be described to determine the magnitude of radiation emitted or incident in a specified direction in space.

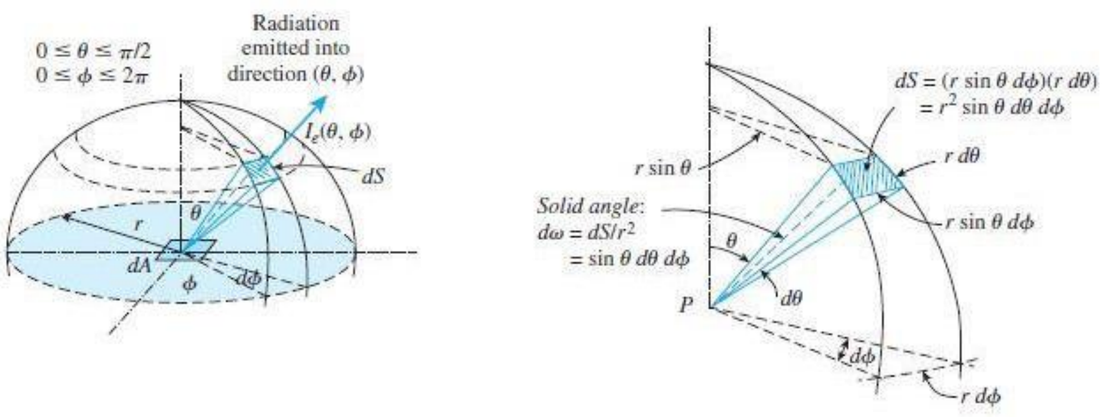

Figure 2.5.3. The emission of radiation from a differential surface element into the surrounding hemispherical space through a differential solid angle

The direction of radiation passing through a point is best described in spherical coordinates in terms of zenith angle θ and the azimuth angle ϕ. The quantity, radiation intensity denoted by I represents how the emitted radiation varies with the zenith and azimuth angles.

As shown in Figure 2.5.3, the angle subtended by an area dS is expressed as differential solid angle, $d\omega$ and it is represented by the following equation;

$$d\omega = \frac{dS}{r^2} = \frac{r^2 sin\theta\ d\theta\ d\phi}{r^2} = sin\theta\ d\theta\ d\phi \qquad (2.5.2)$$

by using the foregoing relation, the radiation intensity for emitted radiation $I_e(\theta, \phi)$ can be defined as the rate at which radiation energy dq is emitted in the (θ, ϕ) direction per unit area normal to this direction and per unit solid angle about this direction. The radiation intensity is given as;

$$I_e(\theta, \phi) = \frac{dq}{dAcos\theta\ d\omega} = \frac{dq}{dAcos\theta\ sin\theta\ d\theta\ d\phi} \qquad (2.5.3)$$

Also, the intensity of radiation is inversely proportional to the distance from source. This phenomenon is called as Inverse Square law.

2.5.3.3 Radiative properties

The emissivity of a surface represents the ratio of the radiation emitted by the surface at a given temperature to the radiation emitted by a blackbody at the same temperature. The emissivity of a surface is denoted by ε, and it varies between zero and one. It is a measure of how closely a real surface approximates a blackbody, for which $\varepsilon = 1$.

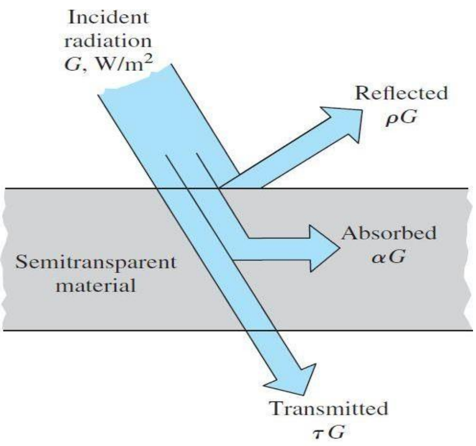

Figure 2.5.4. The absorption, reflection, and transmission of incident radiation by a semitransparent material

Every object is constantly bombarded by radiation coming from all directions over a range of wavelengths as well as emission. Radiation flux incident on a surface is called irradiation and is denoted by G. As shown in Figure 2.5.4, when radiation strikes a surface, part of it is absorbed part of it is reflected and the remaining part, if any, is transmitted. For an opaque medium transmission is not valid and only within a few microns from the surface, a portion of the incident radiation is absorbed. The fraction of irradiation absorbed by the surface is called the absorptivity α, the fraction of reflected by the surface is called reflectivity ρ, and the fraction transmitted is called transmissivity τ.

As expressed in Equation 2.5.4, the summation of these terms will be one.

$$\alpha + \rho + \tau = 1 \qquad (2.5.4)$$

For opaque surfaces, since $\tau = 0$, the foregoing relation reduces to

$$\alpha + \rho = 1 \qquad (2.5.5)$$

For a body with a gray surface (diffuse and its properties are independent of wavelength), the radiation absorbed and the radiation emitted can be given as the following relations;

$$G_{abs} = \alpha G = \alpha\sigma T^4 \quad (2.5.6)$$

$$E_{emit} = \varepsilon\sigma T^4 \quad (2.5.7)$$

Since the surface is gray, emissivity is equal to absorptivity.

2.5.3.4 The view factor

Radiation heat transfer between surfaces depends on the orientation of the surfaces relative to each other as well as their radiation properties and temperatures. To account for the effects of orientation on radiation heat transfer between two surfaces, we define a new parameter called the view factor, which is a purely geometric quantity and is independent of the surface properties and temperature.

The view factor from a surface i to a surface j is denoted by $F_{i\to j}$ or F_{ij} and defined as the fraction of the radiation leaving surface *i* that strikes surface *j* directly.

The view factor from a surface to itself is zero unless the surface sees itself. Therefore, $F_{ii} = 0$ for plane or convex surfaces and $F_{ii} \neq 0$ for concave surfaces, as illustrated in Figure 2.5.6.

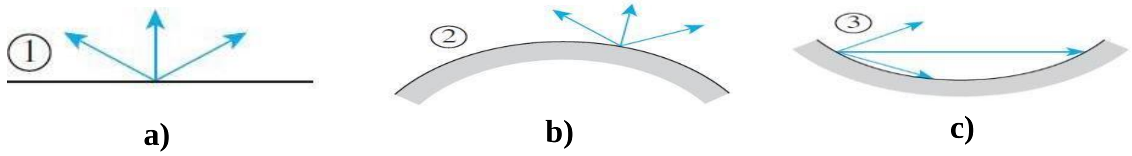

Figure 2.5.5. The view factor from a surface to itself for **(a)** plane surface $\boldsymbol{F_{11} = 0}$, **(b)** convex surface $\boldsymbol{F_{22} = 0}$, and **(c)** concave surface $\boldsymbol{F_{33} \neq 0}$

The Reciprocity Relation

The view factors F_{ij} and F_{ji} are not equal to each other unless the areas of the two surfaces are. That is, $F_{ij} = F_{ji}$ when $A_i = A_j$, $F_{ij} \neq F_{ji}$ when $A_i \neq A_j$. F_{ij} and F_{ji} are related to each other by;

$$A_i F_{ij} = A_j F_{ji} \quad (2.5.8)$$

This relation is known as reciprocity rule.

The Summation Rule

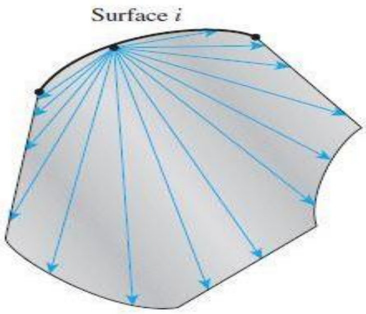

Figure 2.5.6. The radiation leaving any surface i of an enclosure

The conservation of energy principle requires that the entire radiation leaving any surface *i* of an enclosure be intercepted by the surfaces of the enclosure. Therefore, the sum of the view factors from surface *i* of an enclosure to all surfaces of the enclosure, including to itself, must equal unity. This is known as the summation rule for an enclosure and is expressed as

$$\sum_{j=1}^{N} F_{i\to j} = 1 \tag{2.5.9}$$

where N is the number of surfaces of enclosure. For example, applying the summation rule to surface 1 of a three surface enclosure yields

$$\sum_{j=1}^{N} F_{1\to j} = F_{1\to 1} + F_{1\to 2} + F_{1\to 3} = 1 \tag{2.5.10}$$

The summation rule can be applied to each surface of an enclosure by varying *j* from 1 to *N*.

The Superposition Rule

Sometimes the view factor associated with a given geometry is not available in standard tables and charts. In such cases, it is desirable to express the given geometry as the sum or difference of some geometries with known view factors. This method is known as superposition rule.

As shown in Figure 2.5.8, consider a geometry which is infinitely long in the direction perpendicular to the plane of the paper.

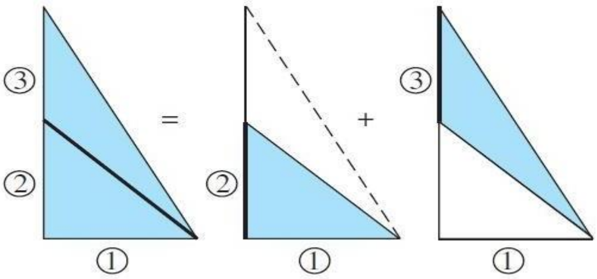

Figure 2.5.7. The view factor from a surface to a composite surface

The radiation that leaves surface 1 and strikes the combined surfaces 2 and 3 is equal to the sum of the radiation that strikes surfaces 2 and 3. Therefore, the view factor from surface 1 to the combined surfaces 2 and 3 is;

$$F_{1\to(2,3)} = F_{1\to 2} + F_{1\to 3} \tag{2.5.11}$$

The Symmetry Rule

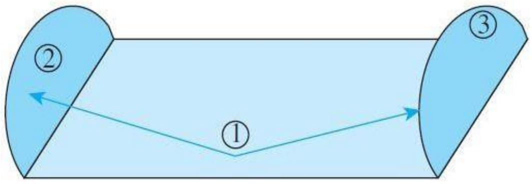

Figure 2.5.8. Two surfaces which are symmetric about a third surface

The symmetry rule can be expressed two (or more) surfaces that possess symmetry a third surface will have identical ciew factors from that surface. If the symmetry rule is applied surfaces as shown in Figure 8, the relation can be stated as

$$F_{12} = F_{13} \; and \; F_{21} = F_{31} \qquad (2.5.12)$$

2.5.3.5 Radiation heat transfer

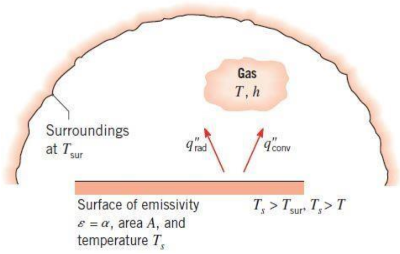

Figure 2.5.9. Radiation heat transfer from a gray surface

When a gray surface of emissivity ε and the surface area A at a thermodynamic temperature T_s is completely enclosed by a surrounding with a temperature of T_{sur}, the net rate of radiation heat transfer between the surface and the surrounding

$$q_{rad} = A(\varepsilon E_b - \alpha G) = \varepsilon \sigma A(T_s{}^4 - T_{sur}{}^4) \qquad (2.5.13)$$

If the surface is black, then $\varepsilon = 1$.

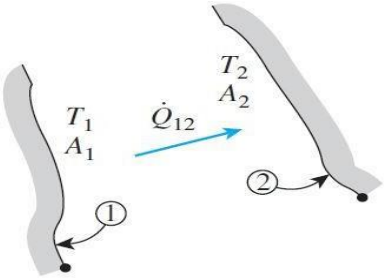

Figure 2.5.10. Two surfaces maintained at uniform temperatures $\boldsymbol{T_1}$ and $\boldsymbol{T_2}$

Consider two surfaces of arbitrary shape maintained at uniform temperatures T_1 and T_2 as shown in Figure 2.5.9. the net rate of radiation heat transfer from surface 1 to surface two can be expressed as the difference between the radiation leaving the entire surface 1 that strikes surface 2 and the radiation leaving the entire surface 2 that strikes surface 1. If the emissivity of the surfaces are the same, the relation can be given as;

$$q_{12} = A_1 \varepsilon E_{b1} F_{12} - A_2 \varepsilon E_{b2} F_{21} \qquad (2.5.14)$$

If the reciprocity rule $A_1F_{12} = A_2F_{21}$ is applied, Equation 2.5.15 reduces to the following relation;

$$q_{12} = \varepsilon A_1 F_{12} \sigma (T_1^4 - T_2^4) \quad (2.5.15)$$

2.5.4.Experiments

2.5.4.1 Experimental setup

The experimental setup includes a horizontal support and a heat radiation source as shown in Figure 2.5.8. Radiometer and other devices related to the experiment can be placed to this support. Radiometer and each device must be placed to relevant holder. These holders can be moved through a rail system.

Heat radiation source gains energy through the measurement and control panel. Temperature of metal plates can be read on the measurement and control panel screen through thermocouples. The signals from radiometer are received through socket *D*.

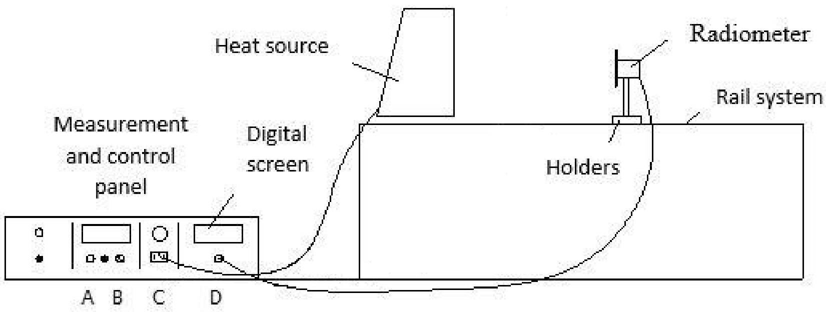

Figure 2.5.11. The experimental setup

2.5.4.2. Determination of Calibration Curve

In order to establish a relationship between a $R\%$ value read from the measurement and control panel and the heat transfer rate received by the radiometer, a calibration curve must be obtained in different heat source temperatures.

Before obtaining the calibration curve, some related terms should be defined. Since the circular plate with a temperature of T_s attached to heat source is black, the heat radiation flux can be obtained by the following formula in case that the surrounding temperature is T_{sur};

$$q_b'' = \sigma (T_s^4 - T_{sur}^4) \quad (2.5.16)$$

and the thermal radiation received by the radiometer which is also at the surrounding temperature is defined as;

$$q_r'' = F\sigma (T_s^4 - T_{sur}^4) \quad (2.5.17)$$

where F is the view factor that represents the fraction of total thermal radiation emitted by circular black plate that received by radiometer or another object. Then the view factor F is defined as;

$$F = \frac{q_r''}{q_b''} \tag{2.5.18}$$

In order to find view factor between circular radiometer and circular black plate, Equation 2.5.19 corresponding to the schematic as illustrated in Figure 2.5.11 can be invoked.

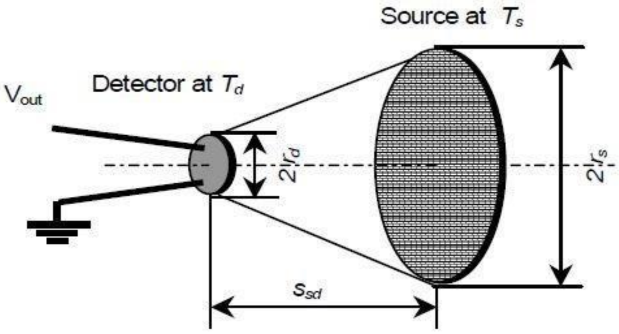

Figure 2.5.12. The circular detector (radiometer) and the circular source

$$F = \frac{2\pi r_d^2}{r_s^2 + r_d^2 + s_{sd}^2 + \sqrt{(r_s^2 + r_d^2 + s_{sd}^2)^2 - 4r_s^2 r_d^2}} \tag{2.5.19}$$

For $T_{sur} = 25.3$ °C, $r_s = 100$ mm, $r_d = 25$ mm and the length of 20 cm between radiometer and detector.

Finally, the relationship between R % and q_r'' (W/m^2) is found as;

$$q_r'' = -0.0069R^2 + 2.0648R - 0.706 \tag{2.5.20}$$

The foregoing relation will be used for all experiments.

2.5.5 Report

1.Cover page.

2. Calculate the experimental and the theorical view factor by using the datas.

3.Discuss the conclusions.