Emissivity Measurements of Reflective Materials using Infrared Thermography

K. Rakrueangdet, N. Nunak, T. Suesut, and E. Sritham

Abstract— **This paper proposes the technique to measure the band emissivity using the infrared detector with a band pass filter of 7.5 to 14 µm. The experimental setup consists of an infrared camera, K-type contact thermocouples, a tripod, a water bath, aluminium plate, a black tape, and an environmental control chamber. Three types of reflective engineering materials including aluminium, stainless steel, and copper are tested using this technique. Results are in good agreement with the findings from other literatures. Therefore, the proposed technique, which is easy to operate, can be an alternative method for measuring the emissivity of reflective materials. However, care must be taken in selecting the location the infrared camera, the material for lining internal surface of an environmental control chamber, and the temperature of chamber surface.**

Index Terms—**Emissivity measurement, Reflective materials, Infrared thermography**

I. INTRODUCTION

THE diagnosis of mechanical and electrical systems in an industrial scale may be performed by measuring the temperature of surfaces, contact spots, or joints. The result could be used for decision making on system maintenance for the sake of safety of processing machine and operators. The temperature measurement may be carried out using a thermal image camera (TIC). The TIC can provide temperature reading values without being in contact with the object. The accuracy of the measurement depends on two input parameters: the emissivity (ε) of the object and the surrounding temperature (T_{surr}). Emissivity is a thermal property of an object that represents the ability to radiate heat. The measurement of emissivity need to consider material type, surface temperature, surface roughness, angle and direction of emission, wavelength or spectral of infrared radiation and the reflection of surface from surround (R), etc. [1]-[5], [7], [9]-[11].

Researchers have employed a number of techniques to measure the ε value of materials. Among these, the technique that takes the reflected temperature from surrounding into consideration has been the most accurate one, though the experimental setup is rather complicated [2]-[5], [7], [10]. Another study reported a considerable error in measuring ε of exterior wall when the reflected temperature from surrounding was excluded from the measurement [4]. The significance of surrounding on the accuracy in measuring ε value depends on the reflectivity (ρ) of the target object [7]. To measure ε, the temperature of the surface has to be higher than that of its surrounding. Accordingly, a sample specimen is commonly heated prior to the measurement. Different heating techniques have been reported in previous studies, e.g., converting electrical energy to heat [3], direct contact heat conduction between heat source and samples [2]-[6]. The later heating technique is subjected to certain limitation in that the sample has to be thin enough so the conduction mainly occurs in one direction. Also, this technique is not suitable for some biological materials, for example, leaves which could be burnt easily. Lopez *et al*. [6] have proposed a technique to heat biological materials using hot water as a heat source. Moist heat does not cause burning. In the studies by Suesut *et al.* [9] and Nunak *et al.* [10], heat was applied to the samples through convection mechanism. It was found that the locations of samples and the design of the environmental control chamber affected the accuracy of measurements. The lining material for the chamber has to be properly selected particularly for glossy sample which would be highly reflective and exhibits a rather low emissivity coefficient. In the experiment where the test temperature is much higher than surrounding temperature, the infrared (IR) window is necessary to maintain the temperature of the environmental control chamber.

The majority of tested samples in prior studies were of a rather low reflective category [6], [11], except in the study by Shi *et al.* [3] where a reflective material like stainless steel 304 was tested using an electrical heating technique. Therefore, this study was aimed at presenting the technique to measure the band emissivity of three different reflective engineering materials including aluminium, stainless steel, and copper using the infrared detector with a band pass filter from 7.5 µm to 14 µm.

II. THEORETICAL BACKGROUND

A. Emissivity

Emissivity (ε) is a surface radiative property, which relates to the amount of radiation or emission from an object. It can be defined as the ratio of energy emitted from a real object (E) and that of a blackbody (E_b) at the same temperature as expressed in (1) [4]-[6], [8], [10], [11], [13].

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$$\varepsilon(T) = \frac{E(T)}{E_b(T)} \qquad (1)$$

Emissivity of each object depends on material type, surface characteristic, angle and direction of emission, wavelength or spectral of infrared, and surface temperature [5], [11], [12]. There are 6 types of emissivity depends on wavelength and direction of the radiation, i.e., (1) spectral directional emissivity, (2) spectral hemispherical emissivity, (3) total directional emissivity, (4) total hemispherical emissivity, (5) band emissivity, and (6) effective emissivity [12]. The typical values of emissivity are presented in Table 1.

TABLE I
EMISSIVITY OF TYPICAL REFLECTIVE MATERIALS

Material type	Wavelength (μm)	Temperature (K)	Emissivity	Ref.
Aluminum	3-5	263-328	0.022	[4]
	total	323-375	0.04-0.06	[13]
	1.5	725-1025	0.03-0.63	[3]
	8-14	323-473	0.39-0.51	[10]
Stainless steel	-	489	0.44-0.60	[14]
	8-14	303-473	0.34-0.52	[9]
	8-14	323-473	0.40-0.52	[10]
Copper	1.5	300-1600	0.04-0.17	[11]
	3-21	523-1173	0.012-0.040	[15]
	8-14	323-473	0.20-0.25	[10]

B. Radiosity

Radiosity (*J*) represents the rate at which all the radiant energy leaving a unit surface area. It is the amount of energy leaving from the target surface. This energy could be detected by IR detectors mounted on a thermal imaging device and consequently converted into a real surface temperature reading value. For gray surface and opaque materials, this radiation includes the reflected portion of the irradiation or reflection (*R*) which depends on its reflectivity (ρ) and surrounding temperature (T_{surr}), and the direct emission from the object surface (*E*) which depends on its emissivity (ε) and surface temperature (T_s). Radiosity can be calculated using (2),

$$J = \varepsilon_s \sigma T_s^4 + \rho_s \varepsilon_{surr} \sigma T_{surr}^4 \qquad (2)$$

where σ is Stefan-Boltzmann constant (5.67x10^{-8} W/m^2·K^4), and the terms $\varepsilon_s \sigma T_s^4$ and $\rho_s \varepsilon_{surr} \sigma T_{surr}^4$ are emission and reflection from target surface, respectively [8], [9], [10], [11].

III. EXPERIMENTS

A. Experimental Setup

The experimental setup (Fig. 1) consists of an infrared camera, K-type contact thermocouples, a tripod, a water bath, aluminium plate, a black tape, and the environmental control chamber. The infrared camera or the thermal image camera (TIC) (Model Ti-400, Fluke Corporation, USA) having a temperature measurement range of -20ºC to 1,200ºC, the accuracy of ±2ºC at 25ºC or 2%, whichever is greater, and the thermal sensitivity of 0.05ºC at 30ºC, was used in this study. The TIC was calibrated with a blackbody (model 9132, HART Scientific, USA) before performing the experiments. The thermal detector is a focal plane array, 320 x 240 pixels with a 24°(horizontal) x 17°(vertical) field of view, spatial resolution (IFOV) of 1.31 mRad at the minimum focus distance of 15 cm. All infrared thermal images obtained from the experiments were analyzed using the thermography software (Fluke SmartView® 3.11).

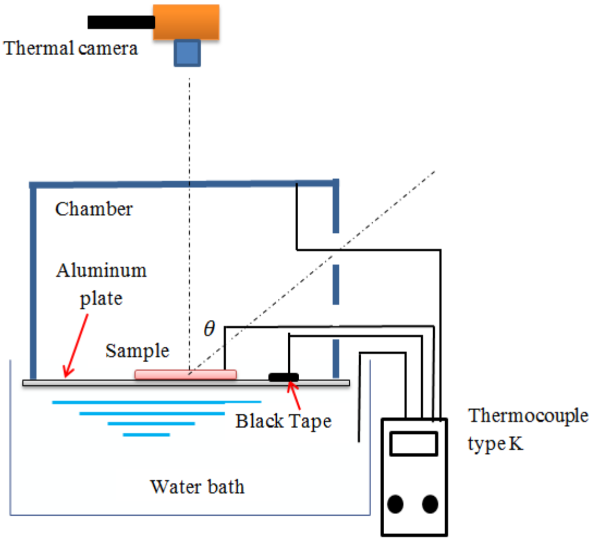

Fig. 1. Schematic diagram of the experimental setup

The temperatures of sample surface, black tape surface, chamber internal surface, and hot water were measured using K-type thermocouples. Hot water was maintained at 85°C. Aluminium foil was used as a lining material for the internal surface of the chamber and an aluminium plate was placed over hot water surface to conduct heat to the sample and the black tape. The reason for choosing aluminium as a surrounding surface was mainly due to its reflective characteristic. Since highly reflective materials exhibit low emissivity, the energy that radiates from surroundings all aluminiunm surfaces, toward the sample would be less. That said the second term in (2) will be small and the obtained *J* value would mainly represent the emission from the target surface.

The TIC was attached to a tripod and located outside the chamber. Due to the fact that infrared is incapable of passing through a solid object, the square openings on the top and the side wall of chamber were made to allow the radiant energy (infrared) to reach the TIC. The locations of the openings were chosen so that the viewing angles of the TIC (θ) were 0°(normal direction) and 30°. A black tape with a known emissivity of 0.95 was used as a reference for the measurements. It was therefore placed on the aluminium plate next to the sample.

B. Measurement Method

Reflective samples in this study were stainless steel, copper and aluminium. Specimens were made as thin slabs with the dimensions of 30 mm x 40 mm.

During the measurement, the sample and the black tape were placed on a thin aluminium plate which was heated with hot water (85°C) in a water bath (Fig.1). Heat conduction through aluminium plate was allowed to reach steady state before taking a measurement. The temperatures of chamber internal surfaces were measured with K-type thermocouples and were averaged as a surrounding temperature (T_{surr}). The T_{surr} was found to be 33±2 °C and it was set in the TIC as a reflection temperature or background temperature throughout the experiments. After the temperature of the black tape surface became steady, it was simultaneously measured with the TIC and K-type contact thermocouple. The temperature value obtained with the thermocouple was set as the actual temperature. The ε value, displayed on the TIC, was adjusted until the temperature measured with the TIC equal to that measured with the thermocouple and the ε value was then recorded.

The emissivity measurement of reflective specimen began from heating the sample and black tape, until the temperature of their surfaces became constant. Then, all infrared radiation (radiosity) leaving from a surface area, based on the FOV specification, and passing through the air was captured by the infrared detector. It had to be sure that the energy emitted from both black tape and targeted sample was detected by IR detector within the FOV area. The percentage of radiative transmission through the air was set at 100%. This means that all energy leaving from the target surface could directly radiate to the IR detector. All of the thermal images captured from the experiments (Fig. 2) were analyzed using the thermography software.

There were two steps in the thermal image analysis. First, the emissivity of black tape (0.95) was set in TIC and the temperature of black tape was recorded. Then, the infrared radiation from the sample surface, covering an approximate area of 2 cm^2 and marked with rectangular frames on every image in Fig. 2, locating close to the black tape, was analyzed. The emissivity value was obtained by adjusting the emissivity of sample using thermography software until the temperature of sample surface measured with TIC equaled to the temperature obtained from the black tape.

During the entire experiment, temperatures of black tape and sample surfaces were also monitored with the thermocouples to assure that temperatures obtained from TIC were in acceptable range. In this study, two viewing angles of 0°(normal direction) and 30° were chosen. The experiment was carried out in triplicate and the average value was taken from the recorded data. Results obtained from the proposed experimental setup were then compared with those in other literatures. Typical thermal images of the tested samples at two different viewing angles are given in Fig. 2.

IV. RESULTS AND DISCUSSIONS

Emissivity is an important parameter used in the measurement of temperature using infrared thermography technique. The accuracy of the obtained temperature value is primarily dependent on how accurately the ε value is known. Researchers have proposed a number of techniques to estimate the ε value of materials. For reflective materials, however, the effect of reflection appears to be the main issue for determining emissivity. According to (2) as previously explained, it could be seen that the ε value of a target sample will be more accurate, if we could control the temperature and emissivity of the surroundings. Therefore, the proposed experimental setup in this study was designed to overcome such issue by using a special designed environmental control chamber to cover the target sample during the measurement. An internal surface of the chamber was lined with aluminium foil, having high reflectivity value, and the measurement was carried out under the condition that the chamber surface temperature was much lower than that of the target sample. Accordingly, the radiation from surrounding would be far lower than the emission from the sample.

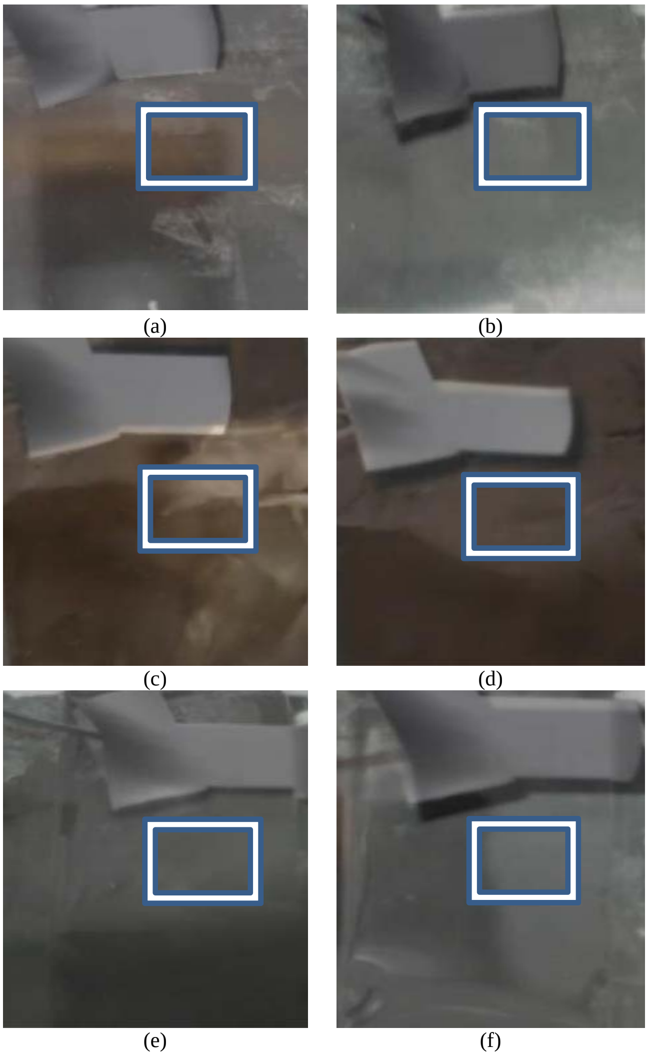
(a) (b) (c) (d) (e) (f)

Fig. 2. Typical thermal images of aluminium plate at (a) $\theta = 0°$ and (b) $\theta = 30°$, copper plate at (c) $\theta = 0°$ and (d) at $\theta = 30°$, and stainless steel plate at (e) $\theta = 0°$ and (f) $\theta = 30°$

Given in Fig. 2 are typical thermal images of the tested samples in grayscale at viewing angle of 0° (normal direction) and 30°. From the image, it could be seen that the black tape exhibited the highest brightness level as compared to other areas of the image. This means the black tape has a higher diffusivity than that of other tested materials. All thermal images of reflective samples obtained in normal direction (Fig. 2-a, 2-c, and 2-e) shows a nonuniform energy radiation due to the effect of reflections. On the other hand, there was no observable effect of reflection on the thermal images at viewing angle of 30^o. After analyzing the images, however, the ε values for all of the reflective samples from both viewing angles were not much different, as presented in Table 2. The results also are in good agreement with those reported by Nunak *et al.* [11]. It would imply that, according to the method used in this study, there was no noticeable interference from surrounding reflection on the captured thermal images. The results obtained in this study falls within a similar range reported in some literatures, showing in Table 1 [9], [10], while the ε values found in other literatures [3], [4], [11], [13]-[15] are considerably different from this study. There are several factors that could be the reason for such difference, say, type of IR detector, band of wavelength, and the operating temperature. Particularly, the operating temperature was quite different between the setting in this experiment and in other studies. Nevertheless, the proposed technique could be an interesting alternative method for measuring emissivity of reflective materials, primarily due to its simplicity. The major concerns for this technique seem to be a temperature setting and a lining material for an internal surface of the chamber. Nunak *et al.* discussed the effects of reflection at different experimental conditions on the emissivity measurement elsewhere [7].

TABLE II
EMISSIVITY OF SELECTED REFLECTIVE MATERIALS

Types of materials	Emissivity at polar angle (θ)	
	0^O	30^O
Aluminium plate	0.26 ± 0.042 (a)	0.26± 0.042 (b)
Copper plate	0.27 ± 0.023 (c)	0.27± 0.038 (d)
Stainless steel plate	0.39 ± 0.026 (e)	0.42± 0.060 (f)

Remark: The letters in parentheses are designated according to Fig. 2.

V.CONCLUSION

The technique to measure emissivity of reflective materials was proposed with a simple experimental setup. The band emissivity of three different reflective engineering materials, including aluminium, stainless steel, and copper, was captured using an infrared detector with a band pass filter of 7.5 µm to 14 µm. The experimental setup consists of seven parts including an infrared camera, K-type contact thermocouples, a tripod, a water bath, aluminium plate, a black tape, and the environmental control chamber. The results are in good agreement with literature values. Care need to be taken into consideration when selecting the location the camera, the lining material for the environmental control chamber, and the temperature of chamber surface. The major advantage of this technique is its simplicity.

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