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ON-LINE MEASUREMENT OF SURFACE TEMPERATURE BASED ON AN INFRARED TARGET

Le Chen [1], Zeyao Wang, Yaqiong Fu, Yunxia Wu, Jianbin Xu

[1] Zhejiang Provincial Key Laboratory of On-line Testing Equipment Calibration Technology Research, China Jiliang University, Hangzhou, China, chenlecjlu@163.com

Abstract − Infrared thermal imager is increasingly used in different fields in production and life, as it possesses the advantages of quick response and non-contact. However, the accuracy of temperature measured by infrared thermal imager is affected seriously by surface emissivity, which limits the use of infrared thermal imager. This paper proposes an on-line measurement of surface temperature by infrared thermal imager based on an infrared target. The experimental results show that the proposed method reduces the error of temperature measurement to about 2%.

Keywords: infrared thermal imager, infrared target, temperature measurement

1. INTRODUCTION

Measuring surface temperature by an infrared thermal imager directly is faster than the general contact temperature measurement, but lower accuracy, especially for the object with bright surface. This is mainly caused by the influence of surface emissivity. Emissivity is also called radiance, blackness, coefficient or emission rate which is a physical quantity to character the infrared radiation ability of the material surface. It is an important thermal parameter and must be set correctly when an infrared thermal imager is used to measure objects' surface temperature, or the measured temperature will be of large error.

In early 1986, a method is proposed to measure the temperature and emissivity of all parts on the production line by using two portable reflector radiation thermometers at the same time. The experiment result showed that the method reduced the error of emissivity measurement within 5% when the temperature is above 400 degrees Celsius and surface emissivity is above 0.6. The method was not very useful at that time not only because the limit of measuring condition, but also the machines were not easy to take [1]. In 1999, Yang Li took the influence of surface emissivity, surface reflectivity, surface absorption, environment temperature, air temperature, atmospheric temperature, atmospheric attenuation and other factors into consideration in the infrared thermal imager temperature measurement. He summarized the influence of these factors on the measurement and figured out the accuracy of measured temperature is greatly influenced by surface emissivity at short distance [2]. In 2010, Hu Jianhong measured three different materials whose surface emissivity is 0.96, 0.93 or 0.3 respectively, and the result showed that a higher surface emissivity led to a better temperature measuring accuracy [3].

In 2011, Wu Yanyan proved veracity of thermal image measuring temperature was mainly influenced by emissivity of object and proposed two methods of calculating emissivity based on thermal image receiving effective radiation. The methods were simpleness and practicality. However, in many sites, the standard temperature in her formula cannot be obtained, that means the methods can only be used in the laboratory measurements [4]. In surface emissivity measurement, there are also many different methods, for example, emissivity on-line measurement apparatus based on front reflector apparatus and optical fiber multi-spectral apparatus, experimental auxiliary and calibration apparatus [5].

Different from the above methods, it is no need to measuring the surface emissivity of the object in the method the paper proposed, but used the infrared target. The paper deals with reducing the impact of surface emissivity on the accuracy of temperature measurement by infrared thermal imager with the design of an infrared target of high emissivity. The design of the infrared target and the measuring system with the infrared target will be explained in chapter 3. The temperature-emissivity model of the method will be explained in chapter 4. In next chapter, the result of the method will be presented. Finally, we will evaluate the proposed method with experimental results.

2. THEORETICAL BACKGROUND

Based on the infrared temperature measurement principle, the reflection and emissivity of objects are diffuse reflection, so the relationship between radiance L and radiant emittance M can be figured out in (1).

$$L_\lambda(n) = M_\lambda(\mathrm{T})\pi \tag{1}$$

According to the Planck's law, the radiation flux F of the thermal imager, which comes from optical system in the surface temperature measure system, can be estimated with the following relationship:

$$F = \tau\pi L_\lambda \,\mathrm{dSsinu} \tag{2}$$

Transmissivity τ of optical system is related to the infrared thermal imager we chose. The opening area S of blackbody, the distance d between the instrument and object, the maximum aperture optical system angle u are shown in Fig. 1.

Assuming that the energy distributed evenly on the cross section as blackbody radiation energy enter the optical system, the illumination can be figured out. Effective radiation consists of self-radiation, environmental reflected radiation and atmospheric radiation as shown in Fig. 2.

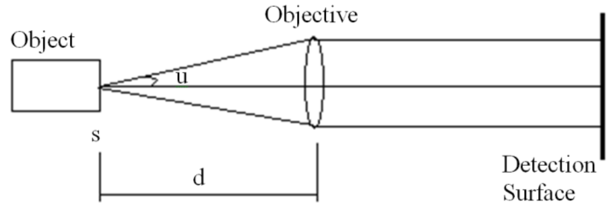

Fig .1 Surface radiation (schematic diagram)

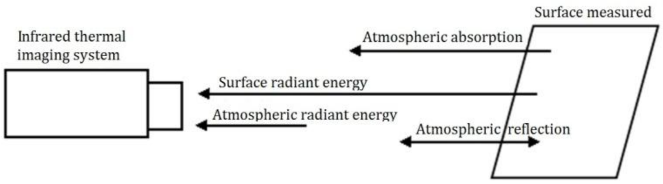

Fig. 2 Effective radiation received by the infrared thermal imager

The illumination E of a wavelength in the detector is given by the following expression (3):

$$E_\lambda = A_0 d^{-2}[\tau_{a\lambda}\varepsilon_\lambda L_{b\lambda}(T_0) + \tau_{a\lambda}(1-\alpha_\lambda)L_{b\lambda}(T_u) + \varepsilon_{a\lambda}L_{b\lambda}(T_a)] \quad (3)$$

where $\tau_{a\lambda}$ is spectral transmittance of atmosphere, $\varepsilon_{a\lambda}$ is the emissivity of atmosphere, ε_λ is surface emissivity, T_0 is surface temperature, T_u is environment temperature, T_a is atmosphere temperature, A_0 is the visual area corresponding to the minimum space angle of the surface measured, d is the distance between the surface measured and the measuring instrument, and A_0d^{-2} is always a constant given by the manufacturer of the instrument.

According to the radiation power incident on the detector, the corresponding voltage signal V_S can be calculated (for instance: [2]) in (4):

$$V_s = A_R A_0 d^{-2}\{\tau_a[\varepsilon\int_{\Delta\lambda}\Re_\lambda L_{b\lambda}(T_0)d\lambda + (1-\alpha)\int_{\Delta\lambda}\Re_\lambda L_{b\lambda}(T_u)d\lambda] + \varepsilon_a\int_{\Delta\lambda}\Re_\lambda L_{b\lambda}(T_a)d\lambda\} \quad (4)$$

Assuming that the object is gray body, atmospheric emissivity can be considered zero and surface emissivity and absorptivity are the same. Now we can conclude the formula of surface emissivity in (5).

$$\varepsilon = \frac{V_s / K - f(\mathrm{T}_u)}{f(\mathrm{T}_0) - f(\mathrm{T}_u)} \quad (5)$$

where K is generally given by the instrument manufactures and f(T) is related to the ability of an infrared thermal imager to change infrared radiation energy into electrical signals.

According to (4), we need to set the emissivity of infrared thermal imager in order to get accurate temperature when we are measuring, if not, we must compensate the value we obtained. And we can figure out the surface emissivity by (5) which is applicable to the vast majority of infrared thermal imagers.

3. DESIGN OF INFRARED TARGET

3.1. Material

The infrared target used in the paper is shown in Fig. 3 and it consists of three parts: high emissivity paint, substrate and adhesive surface. The infrared target will be attached to the object when measuring the surface temperature by an infrared thermal imager. This means that the target should be of high thermal conductivity, good heat resistance and strong viscosity. In this way, the temperature field of the surface measured can be considered equivalent to the temperature field of the target.

Fig .3 Decomposition diagram of the infrared target

The paint is the most important part of the infrared target. It is required to be of high emissivity, stabile emissivity (that is, the emissivity of the paint does not change with the change of temperature) and strong adhesion. What's more, the paint should also dry fast after spraying. The distance from nozzle to the surface sprayed should be from 15cm to 20cm vertically. Before spraying, the paint should be shaken repeatedly so that we can get an even thickness infrared target. We tested a variety of paints and finally chose Japanese black body paint to make the infrared target.

Japanese black body paint is black, made of synthetic resin, colouring agent and organic solvent, and its emissivity is between 0.85 and 0.95. We need to measure the accurate emissivity of the black body paint in the lab before making the infrared target.

The material, which has high thermal conductivity, good heat resistance, smooth surface and low cost, would be chose as the substrate. After testing a large number of materials including copper, red copper, silver, graphite etc., we chose red copper to be the substrate as it has a high thermal conductivity between 388 and 391*W/(m•K)*, and it can withstand the high temperature of 1083℃. In addition, red copper is cheap and easy to get.

The third part of the infrared target is adhesive surface. The adhesive surface needs to be of high thermal conductivity, good heat resistance, strong viscosity and low cost. Finally, we do viscous treatment to single side of the substrate with oleamide and silica gel as the adhesive surface.

The infrared target was made by Japanese black body paint, red copper and glue. The thickness of the red copper is 0.1mm~0.2mm with single sided adhesive. The thickness of the paint is 200~400μm measured by magnetic thickness gauge.

Fig. 4 Measurement of the paint emissivity

3.2. Tests of infrared target

The emissivity of the infrared target is mainly decided by the emissivity of the paint. We measured the emissivity of paint before making the infrared target by using a blackbody chamber and several red copper blocks shown in Fig. 4.

First, the temperature distribution of red copper block surface which is put in the blackbody chamber is tested by several patches of chip platinum resistors.

The Japanese black body paint is sprayed evenly to the bottom of the red copper block which is put in the blackbody chamber at the same location.

The temperature of the bottom surface of the red copper block is measured by an infrared thermal imager with four chip platinum resistors attached to the copper block around.

The emissivity of the paint can be figured out by (5). In (5), the temperatures are measured by the infrared thermal imager, chip platinum resistors and a hygrothermograph.

The thermal conductivity of the infrared target is mainly decided by the substrate. We measured the thermal conductivity of the red copper by a thermal conductivity tester in the lab.

Before taking the infrared target to measurement spot, the correction factor of the infrared target should be figured out by experiment.

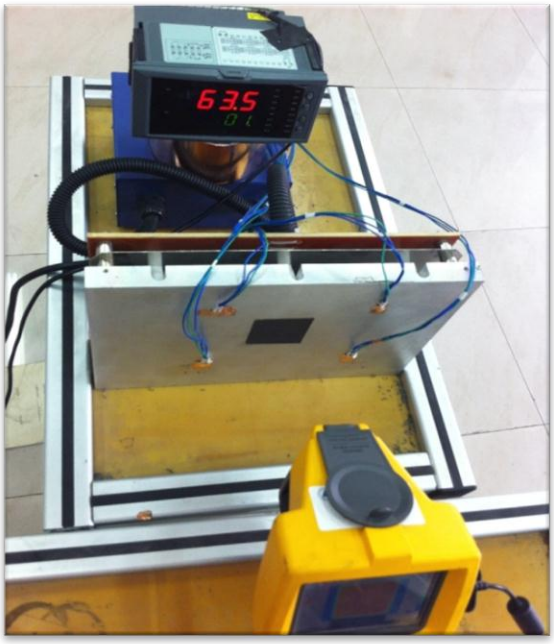

Fig .5 On-line temperature measurement system (Simulation)

4. ON-LINE TEMPERATURE MEASUREMENT SYSTEM

Before measuring, the infrared thermal imager should be calibrated.

The infrared target which was made and tested in the lab is taken to the measurement spot. The relevant on-line temperature measurement device consists of an infrared thermal imager, a hygrothermograph and a computer.

As shown in Fig. 5, in the on-line temperature measurement, the target should be pasted firmly to the object surface measured. Then, carry out the following steps:

a. Measure atmospheric temperature T_u by the hygrothermograph.

b. Measure target temperature T_0' and object surface temperature T_0'' by an infrared thermal imager. The temperature T_0 very closed to the real surface temperature can be figured out in (6).

$$T_0 = f(\varepsilon_0) = \sqrt[n]{(T_0''^{\,n} - T_u^{\,n}) / \varepsilon_0 + T_u^{\,n}} \tag{6}$$

As the target and the object surface are in the same background, same atmospheric environment and have same distance to the instrument, we considered the temperature field of the target and the temperature field of the object measured to be consistent. In this way, the influences of ambient temperature, atmospheric temperature, measuring distance and atmospheric attenuation are avoided.

5. CALIBRATION OF SURFACE EMISSIVITY

The infrared target can not only measure the surface temperature accurately on-line, but also calibrate the object surface emissivity on-line.

In the on-line emissivity calibration, the target should be pasted firmly to the object measured, but after the temperature measurement, the target would be taken down. Detailed steps are as follows:

a. Measure atmospheric temperature T_u by the hygrothermograph.

b. Measure target temperature T_0' and object surface temperature T_0'' by an infrared thermal imager. The temperature T_0 very closed to the real surface temperature can be figured out by (6).

c. Derive the object surface emissivity by the measured temperatures in (5).

d. Take down the infrared target and reset the emissivity in the infrared thermal imager and measure the temperature Tr of object as shown in Fig. 6.

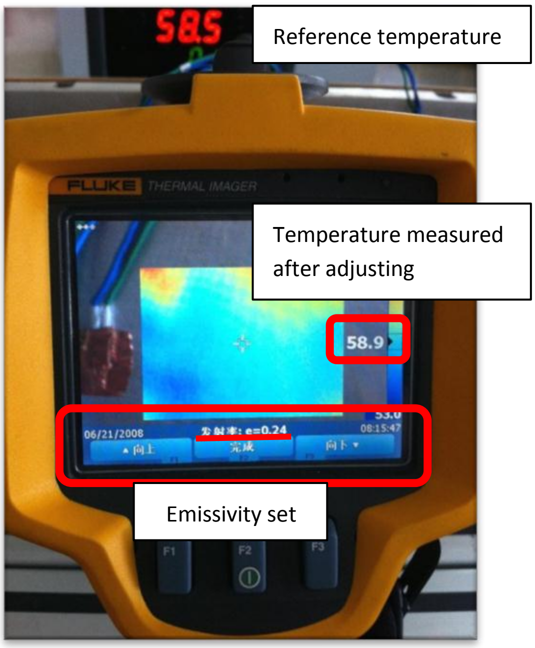

Fig. 6 Calibration of surface emissivity

The method can figure out the object surface emissivity in the on-line measurement quickly and easily.

6. DATA AND RESULT

The emissivity of Japanese black body paint is 0.93 in the range of 0~250℃. Spray Japanese black body paint evenly on a thin red copper sheet. On the other side of the red copper sheet, do viscous treatment with oleamide and silica gel. At this point, the infrared target is completed for use.

In the experiment, iron GC1420 and the aluminum plate were chose to imitate the temperature measurement in industry sites.

Iron GC1420 can automatically adjust the temperature between 60~250℃, its weight is 1.06*Kg* and its power is 1200 *watts*.

Set the iron temperature of 50 ℃, 100 ℃, 200 ℃ respectively and Perform the following steps:

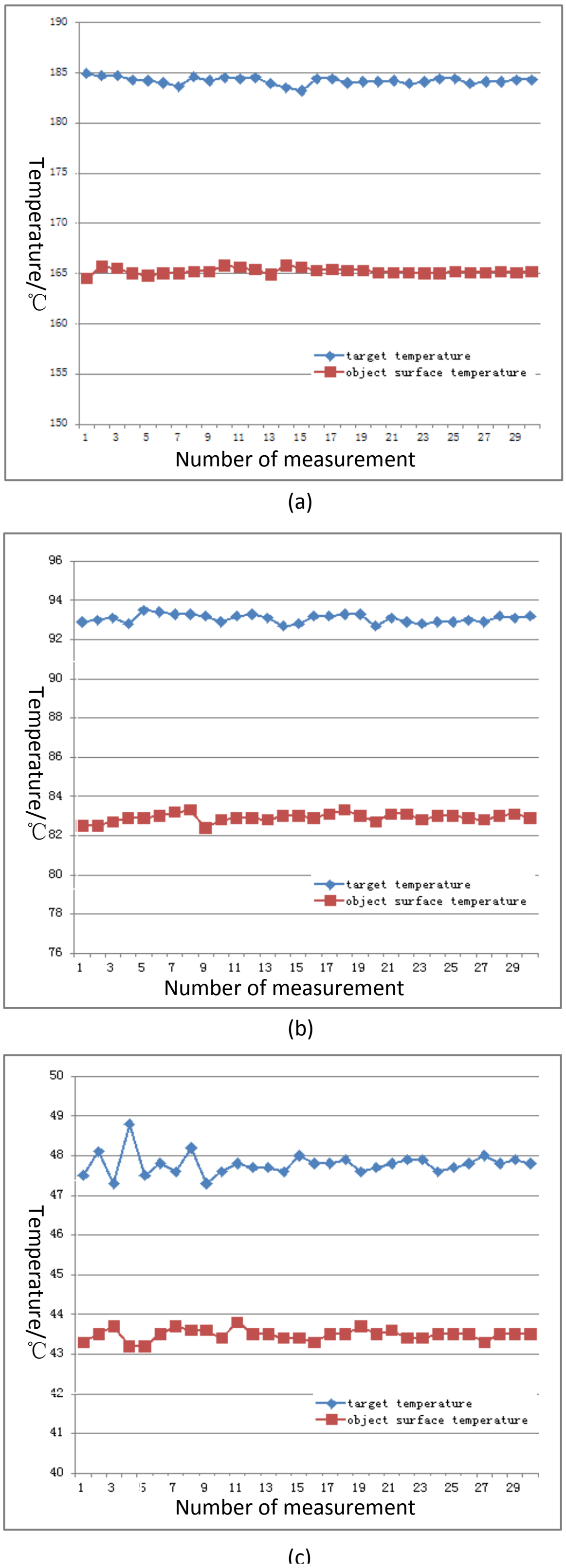

Fig. 7 Temperature lines of the aluminium sheet surface: (a) Set temperature is 200℃, (b) Set temperature is 100℃, (c) Set temperature is 50℃.

a. Attach the infrared target to the iron bottom surface. Keep the target in the same condition of the iron bottom surface.

b. Infrared thermal imager FLUKE Ti25 and DALI DM60-S are used to measure the target temperature. Set the emissivity in the infrared thermal imagers of 1. Record the data and draw the temperature lines in Fig. 7.

The temperature can be regarded as the temperature of the iron bottom surface.

c. Measure the temperature of the iron bottom surface without the infrared target. Figure out the emissivity of the iron bottom surface by (5).

The emissivity of the object measured can be figured out at this moment, and in future on-line measurement, the infrared target is no need to use.

d. Reset the emissivity in the infrared thermal imager and measure the object temperature again.

Taking the averages respectively of the various temperatures and these data are recorded in Table 1. To verify the accuracy of the experiment, A-level platinum resistance patch is used to get the real surface temperature.

Table 1. Temperatures of iron bottom and the emissivity

Set temperature/℃	50	100	200
Target temperature/℃	47.8	93.1	184.2
platinum resistance temperature/℃	48.8	95.3	188.5
Bottom temperature/℃	43.5	82.9	165.2
Bottom emissivity	0.57	0.62	0.64
Calculated temperature/℃	48.4	94.8	187.5

In the lab calibration, the iron bottom real emissivities are 0.6, 0.63 and 0.65 when in the temperature of 50℃, 100℃ and 200℃. The error of the iron bottom surface temperature directly measured is 9%，13%，12% in three different set temperatures. The error of the experiment compared to the platinum resistance temperature is 2%, 1.6% and 1.6% respectively. Error of the temperature measured reduces to less than 2%.

The emissivity measured by the method is 0.57, 0.62 and 0.64 respectively and the error is below 5%.

We also did experiment on the aluminum plate, results shown that the error of temperature measured reduced to less than 2% and the error of emissivity reduced to less than 5%.

7. CONCLUSIONS

The influence of surface emissivity is avoided by using the infrared target in the on-line measurement. In the same time, the influences of ambient temperature, atmospheric temperature, measuring distance and atmospheric attenuation are also avoided as the target is of the same condition of the object to be measured.

The method improves the precision of infrared surface temperature measurement and can be used for the surface emissivity calibration in the on-line measurement.

The experimental results show that the proposed method can reduce the error of surface temperature measurement to 2% and still possesses the advantage of fast temperature measurement of infrared thermal imager. What’s more, the method can measure the surface emissivity of an object accurately and its error is within 5%.

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