Estimation of radiant temperature and emissivity of automobile's surface using infrared thermography

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Abstract: The purpose of this study is to propose a method to determine of surface temperature and emissivity of automobiles. We observed the radiation spectral properties of the surface of automobiles. On the basis of these data, we propose a method to determine the surface temperature and emissivity of automobiles by compensating the reflection of radiant temperature observed by infrared thermography.

Keywords: infrared thermography, automobile, surface temperature, emissivity, heat island

1.Introduction

The heat island in the urban city results from a wide range of factors. From the viewpoint of urban environment planning and architectural planning, the main factors are the following ones:

1) The change of heat balance of urban surface produced by the alteration of land use and land cover,
2) The increase of heat generated by the consumption of energy by buildings and by road traffic.

The heat generated by road traffic is large, not only due to the internal combustion engine but also to the rise of the surface temperature of automobiles. Therefore, influence of road traffic on urban thermal environment and the heat generated cannot be ignored.

To determine the relationship between road traffic and the heat island, the relationship between the quantity of radiation emitted in the atmosphere and the design elements for every type of automobile must be studied. If one were trying to measure the surface temperature of an automobile this could be achieved, for example, by surveying the surface of the automobile with a thermocouple. But, to measure the surface temperature of a multitude of unspecified automobiles in urban areas, this technique isn't realistic. As an alternate method, surface temperature of automobiles can be observed by wide area photography using infrared thermography. However, the problem of this method is that the measurement is influenced by the reflection of long-wavelength radiation from building or sky radiation [1), 2)].

In this paper we propose a method to determine surface temperature and emissivity of automobiles by correcting the reflection of radiant temperature observed by infrared thermography. We discuss the rise of surface temperature of automobiles caused by absorbed solar radiation. The surface of the automobile was divided into three sections: hood, roof and rear window. This is the first stage of a study on the influence of road traffic on the heat island.

2. Radiation spectral properties of the painted surface of automobiles

2.1 Outlines of the experiment

An experiment using an infrared spectrophotometer and a variety of reflective measurement equipment was carried out to investigate the radiation spectral properties for different surface materials, coatings and angles of incidence. Experiments were performed with three types of samples made from fragments of materials from the surface of automobiles: aluminum, steel and plastic. Three tones of paints were studied: black, silver and white.

The experiment was carried out as follows:

1. The emissivity of each material itself was measured to determine its basic emissivity.
2. An experimental sample was coated with a thin coat of paint used for the surface of automobiles and the influence of the emissivity of the support material was studied.

The measurement was made with an angle of incidence of about 0 degrees and 30 degrees to simulate the photography angle used in infrared thermography.

2.2 Characteristics of spectrum radiation spectral properties

We observed the reflectivity of each material and the reflection spectral characteristic of each material in the wavelength band from 3 to 14 micrometers which is used in infrared thermography. The result is shown in Figure 1.

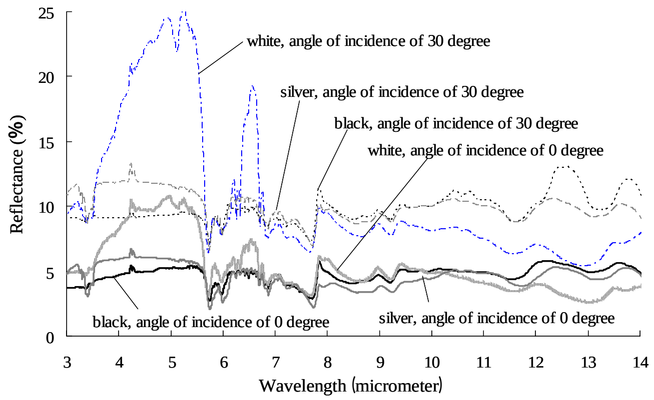
The reflectivity of white paint on aluminum and steel increases rapidly from 3.5 to 6 micrometers and around 6.5 micrometers. The change of reflectivity of aluminum is large up to 8 micrometers but is small from 8 to 14 micrometers. The reflectivity of plastic does not change much from 3.5 to 6 micrometers. The amplitude of the change of reflectivity is larger for plastic than for the other materials between 3.5 and 6 micrometers but it is less different from 8 to 14 micrometers.

Emissivity for different angles of incidence of 0 degrees and 30 degrees and coating materials is shown in Table 1. Emissivity for an angle of incidence of 0 degrees is as high as 93.6 - 95.9%, whereas for an angle of 30 degrees it is only 87.7 - 92.7%. Thus, emissivity decreases by increasing the angle of incidence. Of the three paints, white paint is that with the highest emissivity. Also, emissivity of the painted samples does not depend on the nature of the base material, but only on the color of the paint. Moreover, emissivity at angles of incidence of 30 degrees is constant at about 90 % and the remaining 10 % is reflected. This is the angle of incidence assumed in the measurements by infrared thermography from the building. When observed at an angle of incidence similar to the one used in infrared thermography from the building rooftop, long-wavelength radiation from the wall and the window surface of the opposite buildings is reflected by the surface of the automobile.

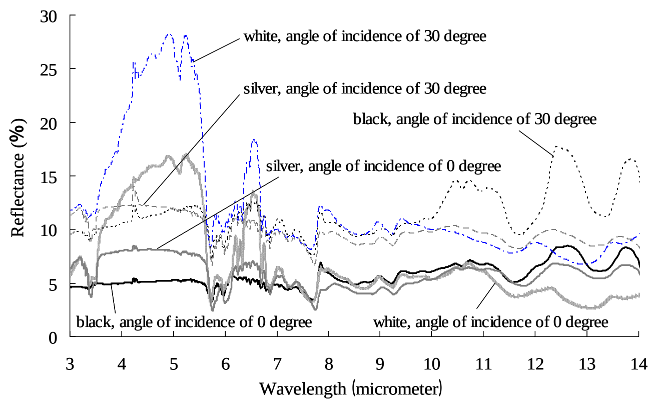
3. Estimation of the radiant temperature of the surface of automobiles using infrared thermography

3.1 Basic concept

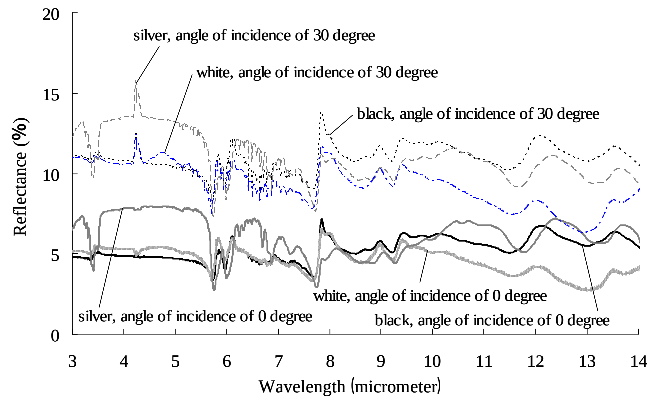
When estimating the surface temperature and emissivity of an automobile using thermal images observed by infrared thermography, it is difficult to specify the object which is reflected on the surface of each part of the automobile. Therefore, we make the following assumptions to remove the influence of the object which is reflected on the surface of each part of the car:



(a) Aluminum



(b) Steel



(c) Plastic

Fig.1 Reflectance for different angles of incidence and coated materials.

Table.1 Emissivity for different angles of incidence and coated materials.

	8-14 micrometer (0 degree)	8〜14micrometer (30 degree)
Aluminum, black	95.1	89.7
Aluminum, white	95.9	92.7
Aluminum, silver	95.6	90.3
Steel,black	93.6	87.7
Steel,white	95.3	91.0
Steel,silver	94.5	90.8
Plastic,black	94.2	88.7
Plastic,white	95.7	91.5
Plastic,silver	94.1	89.7

1) The reflection on the surface of the automobile is a perfectly specular reflection.
2) The long-wavelength radiation of the wall and of the windows of the building, or the sky radiation are reflected on the surface of each part of the automobile.
3) All the surfaces of the automobile and the object which they reflect are gray bodies.
4) The spectral sensitivity of infrared thermography and of radiation thermometer is the same.
Furthermore, the radiation temperature of the object which is reflected on the surface of each part of the automobile was observed from the position of the automobile at the same time.

3.2 Calculation of surface temperature of the automobile

The surface temperature of an automobile's using the specular reflection model is calculated from

$$T_m{}^4 = T_r{}^4 \times (1-\varepsilon) + \varepsilon_s \times T_s{}^4 \quad (1)$$

where T_m: the radiant temperature of the surface of the automobile observed in the thermal image,

Tr : The radiant temperature of the object which is reflected on the surface of each part of the automobile,

ε_s : The emissivity of the surface of the automobile,

Ts: The temperature of the surface of the automobile.

To estimate the reflectivity and the surface temperature, Equation (2) is obtained for the temperature of the surface of the automobile that reflects the wall and the window surface of the building or the sky radiation.

$$T_s = \sqrt[4]{\frac{T_m{}^4 - (1-\varepsilon) \times T_r{}^4}{\varepsilon}} \quad (2)$$

The emissivity and the surface temperature are both unknown quantities in Equation (2). Therefore, calculating the surface temperature of an automobile becomes possible by using this equation for more than two points of the surface where an object from the opposite direction is reflected. As the variable ε_s, the difference of surface temperature of the automobile at each measurement point becomes as small as possible, the emissivity and surface temperature of the automobile are obtained. Correction method A estimates the emissivity and surface temperature of the automobile at several instants in time based on observing thermal images. When measuring the radiation temperature of identical surfaces of the automobile, if the emissivity estimated at every

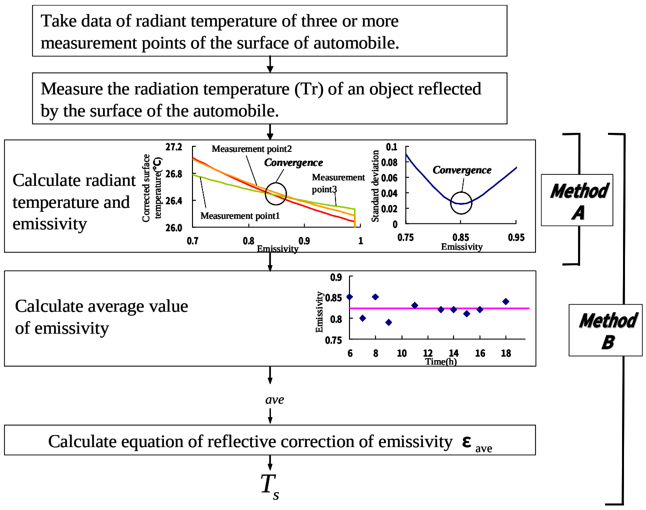


Fig.2 Flow chart of correction.

measurement is equal, it is then possible to assume that the average emissivity is a good value. Correction method B estimates the emissivity and surface temperature of the automobile based on the average emissivity estimated using correction method A. A flow chart of correction is shown in Figure 2.

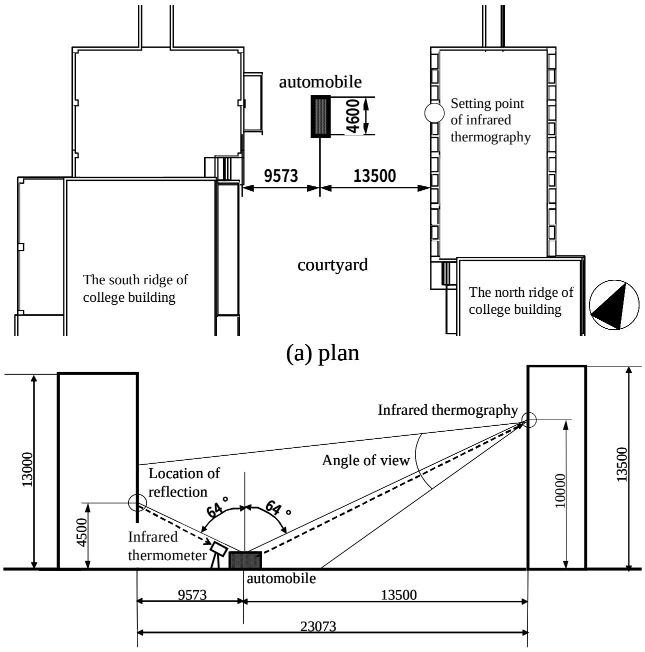
To calculate the surface temperature of the automobile, we assumed the following points.
1) The surface of the automobile reflected a wall and a window surface of the building or the sky radiation.
2) When the calculated surface temperatures converge at more than three measurement points on each part of the surface of the automobile, the correction result is valid.

4. Study of the accuracy of corrected surface temperature of the automobile

4.1 Outlines of the measurement

In order to study the effect of reflection of long-wavelength radiation from the wall and the window surface of the buildings, a thermocouple is attached to the surface of the automobile. We compare the surface temperature of the automobile measured by the thermocouple with the radiant temperature obtained from the thermal image using infrared thermography.

The condition required by the location for the measurement to verify the precision of the radiant temperature of the surface of the automobile after correction, could be as follows:
1) There must be a building with a wall and a window surface that are correctly reflected by the surface of the automobile,
2) There must be a place with a height suitable to install infrared thermography equipment.



(a) plan

(b) section

Fig.3 Place of measurement.

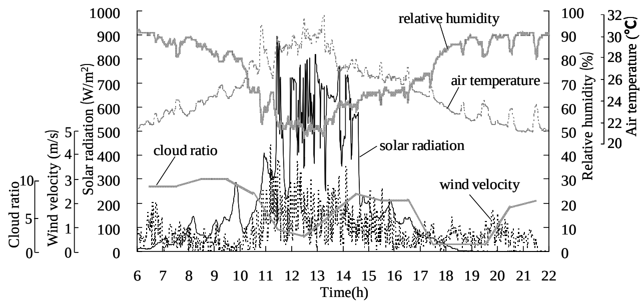


Fig.4 Weather condition on September 16, 2001.

We selected a courtyard in the Niigata Institute of Technology. The college building is separated into a south ridge and a north ridge. Setting an automobile in the courtyard, the surface of the automobile reflects long-wavelength radiation from the wall and the window surface of the college buildings, or the sky radiation. Therefore, the object reflected by the surface of the automobile can be easily specified. Figure 3 shows the configuration of the location of the measurement.

An identification measurement was carried out in a courtyard at the Niigata Institute of Technology, Niigata Prefecture, Japan, from 6:00 a.m. to 10:00 p.m. on September 16, 2001. We observed a thermal image of the surface of an automobile and of buildings at hourly intervals using infrared thermography in the 8 to 14 micrometer band. The specification of wall and window surface reflected by the surface of the automobile was observed by direct viewing and by taking photographs of the surface of the automobile using a digital camera. The radiant temperature of the wall surface of the building was measured at hourly intervals using a radiation thermometer. The body color of the automobile was black. The surface temperature of each part of the automobile and of the wall surface of the building was measured by a thermocouple. Temperature inside the car was controlled by adjusting air conditioning to 25 degrees Celsius.

Fig.5 Examples of thermal images observed at 9:30 on September 16, 2001.

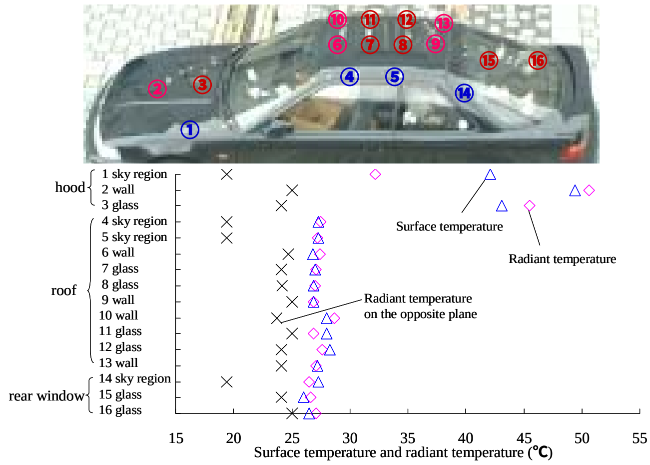


Fig.6 Relation between radiant temperature and radiant temperature of each measurement points.

4.2 Survey results

Figure 4 shows the weather condition. The highest value of air temperature was 31.8 degrees Celsius. Wind speed was over 3 m/s from 11:00 to 14:00.

Figure 5 shows examples of thermal images observed by infrared thermography at 9:30. The surface of the automobile observed in the thermal image shows the reflection of the wall and window surfaces of the building, and thus, the radiation temperature of the surface of the automobile was low.

We defined three points on the hood and on the rear window and 10 points on the roof, and we measured the radiation temperature at the measurement points observed in the thermal image. For example, the relation between the radiation temperature and the surface temperature of each measurement point at 8:30 is shown in Figure 6. The radiation temperature of the roof was lower than its surface temperature. The reason is that the roof reflected a wall surface and a window surface of the building which were at a low temperature. Also, the radiation temperature and the surface temperature of the rear

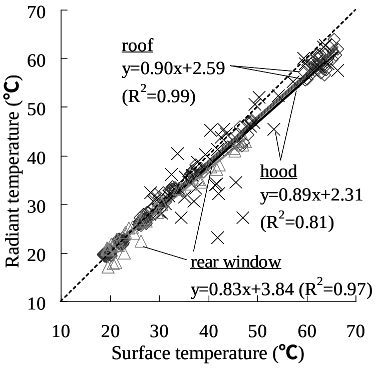


Fig.7 Relation between surface temperature and radiant temperature.

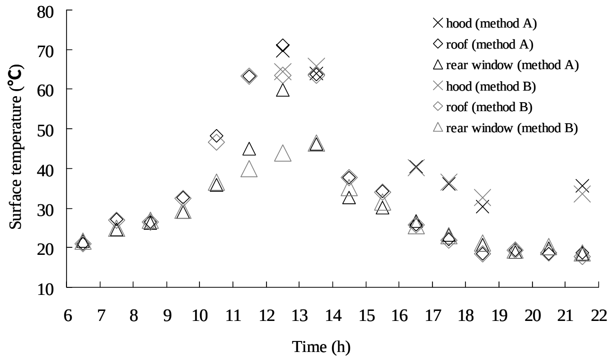


Fig.8 Surface temperature of automobile's surface.

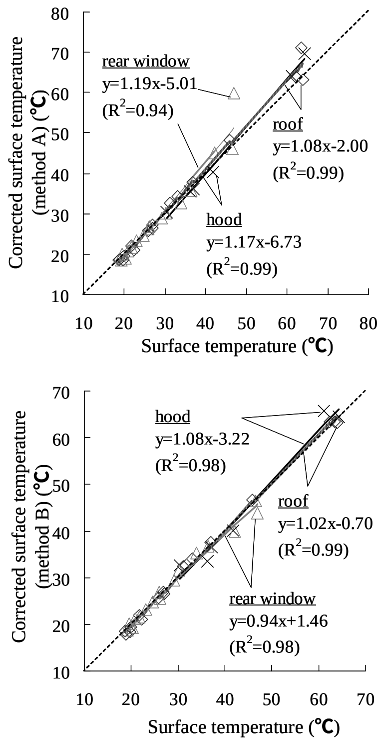


Fig.9 Comparison of surface temperature and corrected surface temperature.

window and of the hood were about the same because neither the rear window nor the hood reflected a wall or a window surface of the building.

Figure 7 shows the relation between radiation temperatures observed by infrared thermography and surface temperatures measured by the thermocouple on each part of the surface of the automobile. The radiation temperature is lower than its surface temperature because the surface of the automobile reflected a wall surface and a window surface of the building which were at a low temperature.

4.3 Correction result

We estimated radiant temperatures by making corrections according to the flow chart shown in Figure 2 using the radiation temperature observed by infrared thermography. Figure 8 shows the diurnal change of surface temperature of the automobile corrected using correction method A and correction method B. The average of the emissivity of the roof over a day used for correction method B was 0.83; for the hood it was 0.79, and for the rear window, it was 0.78. The standard deviation of the emissivity of the roof was 0.08, for the bonnet it was 0.09, and for the rear window, it was 0.15. In each part, the surface temperature of the automobile obtained using correction method A was higher than that obtained using correction method B. From 11:00 to 13:00, the difference between the surface temperature of the automobile obtained using correction method A and correction method B became larger.

Figure 9 shows the relation between surface temperature corrected by correction method A and correction method B and surface temperature measured by the thermocouple. Corrected surface temperatures and surface temperatures measured by the thermocouple agree almost perfectly as shown by the linear regression. We used the coefficient of linear regression to evaluate the accuracy of the correction. The coefficient of linear regression of correction method A is higher than in the case of no correction. The coefficient of linear regression of correction method B is higher than for correction method A and the accuracy is satisfactory. The convergence point would increase if the number of measurement points were increased, so the accuracy of correlation could be improved.

4.4 Relation between temperature distribution of the surface of the automobile and weather condition

To examine the relationship between temperature distribution of the surface of the automobile and weather condition, we obtained a relation between solar radiation and the difference between surface temperature of each part of automobile and air temperature. These relationships are depicted in Figure 10. Of the three parts of the automobile, the hood exhibits the highest values of difference between surface temperature and air temperature. For each part of the surface of the automobile, a linear regression can be obtained with solar radiation and the coefficient of correlation is more than 0.8. This result shows that surface temperature of an automobile can be explained in terms of the incidence of solar radiation and air temperature.

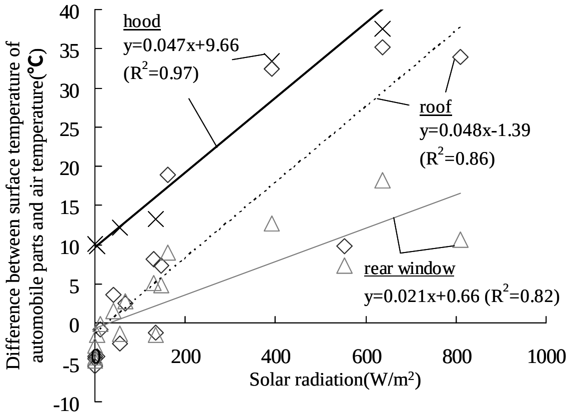


Fig.10 Relation between solar radiationand difference between surface temperature of automobile parts and air temperature.

5. Conclusion

1) An experiment using sample fragments of the surface of an automobile was performed to investigate the radiation spectral properties as a function of surface material, coating and angle of incidence. Long-wavelength from the wall and the window surface of the buildings is reflected by the surface of the automobile when observed at an angle of incidence similar to the one used in infrared thermography from the building rooftop.
2) We proposed a method to estimate surface temperature and emissivity of an automobile by compensating reflection of radiant temperature observed by infrared thermography. Surface temperature and corrected surface temperature of the automobile agree quite well and the effectivity of this method was thus shown.
3) For weather conditions where the wind speed is weak in the daytime of the summer, the surface temperature of parked automobiles could be explained in terms of the incidence of solar radiation and air temperature.

Future research will address the following problems: (a) the development of a model which shows a relation between weather conditions and the surface temperature of the automobile for every type of automobile and paint; and (b) the development of modeling of heat generated from road traffic including the relation between the running condition of the automobile and gasoline consumption.

Acknowledgement

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