Measurement of Thermal Radiation Properties of Large Heating Equipment Using Infrared Thermography

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ABSTRACT

Most modern houses no longer use traditional heating systems (e.g., the fireplace, stove, the pechka, the ondol, and the kotatsu) and instead rely on mechanical heaters, as the latter have greater functionality and more features. However, as the traditional systems use wood, a natural energy resource, they are more suitable for reducing the consumption of fossil fuels. Further, they provide a unique sensation of warmth as they dissipate heat through thermal radiation.

In this study, in order to reevaluate the heating characteristics of traditional heating systems that use wood, we devised a new method for measuring their thermal radiation properties. On the basis of the concept of the luminous intensity distribution, we defined the "thermal radiant intensity distribution," which is calculated by integrating the luminance of thermal radiation in each direction. A thermal image is constructed by assembling pixels representing the surface temperatures determined from a parallel projection of the heating equipment. Hence, the luminance of thermal radiation could be found for all the directions from the pixels to the observer.

We employed the proposed method to investigate a large firewood stove in operation in the winter, and determined its thermal radiant intensity, which was found to be 47–121 W/sr; this value is much greater than that of an electric heater (an 800 W electric heater has a thermal radiant intensity of 15 W/sr). It was assumed that, as traditional heating systems do not include a fan, larger systems are installed within the building structure and warm not only the air with the rooms but also the room surfaces, such as the walls, floors, and ceilings.

INTRODUCTION

In most modern houses, traditional heating equipment (e.g., the fireplace and stove in European countries, the pechka in Russia, the ondol in Korea, and the kotatsu in Japan) has been replaced by mechanical appliances such as air conditioners and fan heaters because of their better functionality and useful features. However, as traditional equipment use wood-based biomass, including firewood and wood charcoal, which are natural energy resources, they hold more potential in the near future from the view point of reducing fossil fuel use. Further, they also provide a unique sensation of warmth, owing to thermal radiation. For example, just after the Great East Japan Earthquake in 2011, firewood stoves were in high demand, especially in the arenas where the refugees lived for a few months in the winter season.

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The reason for this was not that the supply of other fuels was limited but rather that the heating capability of the stoves was better. It is for this reason that we have chosen to investigate the thermal radiation properties of traditional heating equipment.

Figure 1  Firewood piled up under the eave of a traditional Japanese house.

1. EXOTHERMIC CHARACTERISTICS OF TRADITIONAL HEATING EQUIPMENT

Takamiya et al. have classified the heating equipment installed in vernacular architecture in Eurasia into Types #1 to #12 on the basis of their design characteristics, including factors such as whether the hearth is enclosed, where the exothermic part (i.e., the area, device, or unit from which the heat emitted) is located, whether it has a chimney, and what is its relation to the building. Developing this idea a little further, we have added the method of heat transfer to the classification system and reordered the types, deleting Types #6 and #7, as shown in Table 1.

With respect to the heating capability, Types #2 and #3 produce lower amounts of heat because these equipment pieces are "movable" and can be located in different places in the house, depending on the conditions. The "unified" types are graded from Type #1 to Type #12, that is, from "open" to "closed" on the enclosure of the hearth and "just around the hearth" to "dedicated part (in the next room)" on the exothermic part; these heaters are greater in size and have higher efficiencies. All the types except for Type #10 either do not have chimney or have an indoor one. Further, for all equipment types, heat transfer occurs through "radiation" or "conduction." Modern mechanical heaters, which are small and high-powered in comparison, distribute heat by blowing warm air in the room. As traditional heating systems do not include a fan, larger pieces of equipment are usually installed within the building structure to warm not only the air in the rooms but also the room surfaces, such as the walls, floors, and ceilings.

<table>
<thead>
<tr>
<th>Type</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#5</th>
<th>#4</th>
<th>#8</th>
<th>#9</th>
<th>#11</th>
<th>#10</th>
<th>#12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heater</td>
<td>Open hearth</td>
<td>Brazier</td>
<td>Kotatsu</td>
<td>Stove</td>
<td>Fireplace</td>
<td>Pechka</td>
<td>Kang</td>
<td>Kachel-ofen</td>
<td>Ondol</td>
<td>Kang</td>
</tr>
<tr>
<td>Enclosure of the hearth</td>
<td>--- Open ---</td>
<td>--- Closed ---</td>
<td>Semi-Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Part of the exothermic</td>
<td>Just around the hearth</td>
<td>Dedicted part</td>
<td>Dedicated part in the next room</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chimney</td>
<td>Without chimney</td>
<td>Indoors</td>
<td>Indoors</td>
<td>Outdoors</td>
<td>Indoors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relation to building</td>
<td>Unified</td>
<td>Movable</td>
<td>Fixed</td>
<td>Unified</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Method of heat transfer</td>
<td>Radiation</td>
<td>Convection and Radiation</td>
<td>Radiation</td>
<td>Convection and Radiation</td>
<td>Convection, Radiation, and Conduction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2. METHOD FOR EVALUATING THERMAL RADIATION PROPERTIES USING INFRARED THERMOGRAPHY

2.1 Thermal imaging

To determine the warmth-producing abilities of traditional pieces of heating equipment that make use of radiation and conduction rather than convection for heat transfer, as mentioned in Chapter 1, where the concept of luminous intensity (cd(= lm/sr)) distribution was described, we calculated their "thermal radiant intensity (W/sr) distributions." The thermal radiant intensity distribution of a heating system is a thermal radiation property and is obtained by integrating the luminance of thermal radiation (W/(sr m²)) in every direction. The thermal radiant intensity for a specific direction is measured as follows:

1. Obtain thermal images using an infrared thermography system (i.e., a thermocamera) from a position at a specific distance from the center of the target heater. The nearer one is to the heater, the more detailed is the image obtained. However, if one is too near, the image will be distorted, in contrast to the image obtained from a parallel projection, because of the wide visual angle. However, it is difficult to keep the object distance large when photographing in the up/down directions. To ensure that the entire target heater was in the eyeshot of the thermocamera (horizontally 21.7° × vertically 16.4°) and to maintain the object distance at a reasonable value, we set it to 1.5 m.

2. Photograph the front side and in all the directions of the horizontal/vertical sides in steps of 22.5°. That is to say, photograph in 16 directions for each aspect, for a total of 41 directions (= (16 × 3) – 6 – 1), while excluding the 6 duplicated intersections and the upward view from below. If the shape of the heater is symmetric, it is enough to photograph 28 directions (= 41 – 1 – (3 × 4)).

3. Project the image of the concentric circles and radial lines on a wall of the room in which the photographs are being taken. Set the thermocamera at the intersection of these lines to pinpoint the object distance and the photography direction. We projected only one-fourth of the concentric circles (see Figure 2). Changing the top/bottom and the right/left directions allowed us to take photographs in limited space.

![Image of a thermocamera and a wall](image.png)

Figure 2 Procedure for obtaining the thermal image: the thermocamera is located at an object distance of 1.5 m; this can be confirmed from the shadow on the wall.

2.2 Calculating the thermal radiant intensity

If one considers a thermal image as a set of the surface temperature data that is the parallel projection of a heater, the thermal radiant intensity (W/sr) can be obtained by summing the luminance of the thermal radiation (W/(sr m²)) from each pixel of the thermal image of the entire target heater to the observer, that is, in the direction normal to the thermal image (see Equation (1)). The denominator "\( \frac{2\pi}{4} \)" in Equation (1) represents the whole solid angle (sr) of the thermally imaged surface.
3. MEASUREMENT OF THERMAL RADIATION PROPERTIES OF A LARGE FIREWOOD STOVE

3.1 Background for proposing a novel measurement method

The method described in Chapter 2 for measuring the thermal radiation properties has the following limitations:

1. It requires that the heater to be imaged be placed at a certain distance so that the entire heater fits in the eyeshot of the thermocamera.
2. The directions for which we can measure the thermal radiation properties using thermocamera are limited.

However, most traditional heating systems are large. Therefore, using this method, it is not possible to evaluate the thermal radiation properties in smaller houses as well as one can in the case of large houses.

3.2 From thermal imaging to thermal solid figures

Using the photogrammetry software "SurveyFromPhoto," it is possible to construct thermal solid figures from thermal images. We constructed thermal figures using bitmapped images with a 256-value palette. A heater and its thermal solid figure are shown in Figures 3 and 4, respectively. When constructing the thermal figures, the following four steps have to be followed, as per the specifications of SurveyFromPhoto. It should be noted that a thermal image has fewer pixels and colors than does an optical image. That is to say, it does not seem to have a third dimension.

1. The target can be photographed at any distance and from any direction and position. However, SurveyFromPhoto requires that each image has more than ten identity points. Further, among these, more than four of the identity points should be enclosed in several different images.
2. Before photographing the heater, place a piece of aluminum on any sharp edge or protrusion on the body of the heater so that its shape is visible and the identity points can be set with precision. Then, photograph the heater against a background of a different temperature.
3. Take photographs from each direction in front of the aluminum piece so that the identity points are distributed stereoscopically, as this will allow a precise solid figure to be constructed.
4. Take photographs from each direction in front of the major plane so that distortion-free images can be obtained to form the polygons that are used to construct the solid figure.

Figures 3 and 4  Photograph of the investigated electric heater (power of 800W) and its thermal solid figure.

\[
E = \sum_{i} \frac{\sigma T_i^4 S_i}{2\pi} \quad (1)
\]
3.3 Calculating the thermal radiant intensity

To calculate the thermal radiant intensity, Equation (1) can be used, provided the area of the pixels is determined as follows:

1. Push the PrtScn key on the keyboard when a thermal solid figure is displayed in the direction in which the thermal radiant intensity is to be calculated, and open a copy of the image in the GNU Image Manipulation Program (GIMP).
2. Count the number of the pixels corresponding to the length of the reference line indicated in the image, and calculate the area of a single pixel \( (m^2) \) using Equation (2).
3. Erase all the pixels from the image, except those representing the target heater, either using the "fuzzy select" function of GIMP or manually (i.e., erase the pixels one by one), if necessary.
4. Save the image, which is now of only the target heater, in the BMP format and convert it to the CSV format using the software BMP2CSV, which allows one to change data formats.
5. Open the CSV file in Excel. The temperatures corresponding to the individual pixels can be found from the values in the spreadsheet and the color scale of the thermal image.

\[
S = \frac{L^2}{N^2} 
\]  

(2)

3.4 Characteristics of the measurement method

When using the measurement method described in Chapter 2, the amount of thermal radiation emanating from the heating equipment is measured directly. Therefore, we can determine the actual values. On the other hand, in the case of the method described above, a thermal solid figure constructed using a software program is used as a virtual heater and is used for the measurements. Therefore, one can call the former method a direct one and the latter an indirect one.

The differences between the direct and indirect methods are listed in Table 2. The advantages of the indirect method are that the object distance and direction can be changed freely when taking the photographs. This makes it possible to photograph heaters in small rooms quickly. There are also a few disadvantages in that a number of different software programs are needed for the calculations. It should be noted that the distance for calculating the thermal radiant intensity, which is correlated to area of the pixels, is finite in the direct method, in which it is considered the object distance. On the other hand, it is infinite in the indirect method because the image constructed using SurveyFromPhoto is based on orthogonal projections. There is also a difference in the metric used to determine the size of the heating equipment. The solid angle (sr) is used in the direct method, while the projection area \( (m^2) \) is employed in the indirect method. Hence, it may be said that the two methods are quite different.

| Table 2. Comparison of the direct and indirect measurement methods |
|---------------------------------|-----------------|-----------------|
| **Method**                     | **Direct**      | **Indirect**    |
| Target for measuring           | Heating equipment | Thermal solid figure built using a software program and used as a virtual heater |
| thermal radiant intensity      | Distance at which the entire target heater fits in the eyeshot of the thermocamera | Actual distance, which depends on the space available in the room |
| Object distance                | Direction of measurement | Actual direction for constructing the thermal solid figure |
| Direction of photography       | NS9200 (NEC)    | NS9200 (NEC)    |
|                                | Excel (Microsoft) | Excel (Microsoft) |
|                                |                  | SurveyFromPhoto (Freeware) |
|                                |                  | GIMP (Freeware)   |
|                                |                  | BMP2CSV (Freeware) |
3.5 Comparison of the results obtained using the direct and indirect methods

Figure 5 shows the thermal radiant intensities of the heater shown in Figure 3 as measured using the direct and indirect methods. The solid angle and thermal radiant intensity/solid angle ratio determined using the direct method, as well as the projection area and luminance of thermal radiation are also shown in the figure.

On comparing the thermal radiant intensity distributions obtained using the two methods, it was found that the distributions had similar shapes (oval) on the elevation side. However, the directions of the peaks on the sectional and horizontal sides were different. The maximum intensity was noticed in front of the heater, that is, at #13 in Figure 5, when using the direct method, while a gap of 22.5° or 45° existed when using the indirect method. This is because the grille and fire back do not affect the results obtained using the indirect method. That is to say, an exact heating element was not built in the virtual thermal solid figure but was represented by a thermal image plane instead. The difference in the thermal radiant intensities obtained using the two methods was less than 1.5 W/sr (i.e., 17%).

Further, on comparing the parallel values, that is, the thermal radiant intensity/solid angle ratio obtained using the direct method and the luminance of thermal radiation determined using the indirect method, the directions of the maximum/minimum values were similar. Thus, it can be surmised that the indirect method is suitable one.

![Figure 5](image)

**Figure 5** Comparison of the results obtained using the direct method (left) and the indirect method (right).

3.6 Thermal radiation properties of a large firewood stove

3.6.1 Measurement procedure. We employed the indirect method to measure the thermal radiation properties of a large firewood stove used routinely in the house. The target stove had a well-
designed but complicated shape, as shown in Figure 6. The measurement was performed under the conditions listed in Table 3. Several kinds of air-dried firewood, such as Japanese cedar, cherry, sawtooth oak, and zelkova, to name a few, but not pine, were burned as per usual use. As can be seen from the thermal image in Figure 7, the surface temperature of almost the entire stove exceeded the upper limit of the range of the thermo camera (120 °C). Even though the stove was installed in a large room of a detached Japanese house, it was in a corner surrounded by houseplants and pieces of furniture. Therefore, the area that could be photographed was restricted.

3.6.2 Measurement results. The thermal radiant intensity, projection area, and luminance of thermal radiation of the large firewood stove are shown in Figure 8. The most important point to note is that the thermal radiant intensity was determined to be 47–121 W/sr, which is much greater than that of an electric heater (an 800 W electric heater exhibits a thermal radiant intensity of 15 W/sr). The main reason for this is that the entire surface of a stove is an exothermic area, and a large stove has a large area. Because the upper limit of the temperature range of the thermocamera was 120 °C, the thermal image obtained could not have indicated higher temperatures. However, if one assumes that the internal temperature of the stove was 200 °C, the thermal radiant intensity would be more than 2.1 times higher, as per Equation (1).

Table 3. Measurement conditions

<table>
<thead>
<tr>
<th>Date and time</th>
<th>Weather</th>
<th>Location</th>
<th>Indoor air temperature and relative humidity</th>
<th>Outdoor air temperature and relative humidity</th>
<th>Area of the room</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan 26, 2011</td>
<td>Fine</td>
<td>Detached house in Sendai, Japan</td>
<td>22.4 °C, 43% on average</td>
<td>6.2 °C, 42% on average</td>
<td>Main room with wellhole: 45.8 m²</td>
</tr>
</tbody>
</table>
CONCLUSION

In this study, we proposed direct and indirect methods for measuring the thermal radiation properties of traditional heating equipment. Using the indirect method, we measured the thermal radiant intensity distribution of a large firewood stove and found that it radiated a large amount of thermal radiation. Shukuya has noted that using radiant warm exergy for heating purposes is more effective than using convective warm exergy as the former results in both greater thermal comfort and a low human-body exergy consumption rate. It is likely that the exergy consumption rate is a function of the quality of the warmth. The high thermal radiant intensity of the stove allowed it to not only warm the air in the room but also the room surfaces, such as the walls, floors, and ceilings. This probably accounts for the uniqueness of the warmth generated by traditional heating equipment. An exploration of type of walls and ceiling finishes should lead to a better understanding on how living spaces are heated through heat reflection/convection. We intend to pursue these goals in a future study.

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NOMENCLATURE

\[ E = \text{thermal radiant intensity (W/sr)} \]
\[ L = \text{length of reference line (m)} \]
\[ N = \text{number of pixels corresponding to the length of reference line} \]
\[ S = \text{area of a pixel (m}^2\text{)} \]
\[ T = \text{temperature of a pixel (K)} \]
\[ \sigma = \text{Stefan-Boltzmann constant (}=5.67 \times 10^{-8}\text{)} (\text{W/(m}^2\text{K}^4)) \]

Subscripts

\[ i = \text{pixel index number} \]

REFERENCES

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