Sensor specifications for in-situ measurement of the temperature distribution inside the wall material for evaluating thermal performance of residential buildings

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Abstract. It is important to measure and ensure the thermal insulation performance of newly built or existing residential buildings to promote energy-efficient and comfortable housing throughout society. Among various in-situ measurement methods for this purpose, this study focuses on the probe insertion method, in which a borescope and a temperature sensor are inserted through a tiny hole drilled in the interior side of the wall to visually inspect and measure the temperature distribution inside the wall. In this method, the temperature sensor itself can act as a thermal bridge, which causes a deviation from the original temperature distribution inside the insulation material. In this paper, based on physical considerations and heat conduction simulation, we introduce two dominant dimensionless numbers that determine the temperature deviation: the Biot number and the newly defined \( N_c \) value. In addition, we draw schematic charts to find the temperature deviation from the introduced dimensionless numbers, and suggest a procedure to determine the required specifications of a temperature sensor that can accurately measure the temperature distribution.

1. Introduction

The thermal insulation of residential buildings affects the energy use for heating, especially in winter, and influences the strength of cold drafts near the exterior walls, which in turn affects indoor thermal comfort. Therefore, it is important to measure and ensure the thermal insulation performance of newly built or existing buildings to promote energy-efficient and comfortable housing throughout society. Various in-situ measurement methods have been proposed for this purpose. Huertas et.al. [1] reviewed in-situ measurement methods for assessing the thermal transmittance of walls, such as the heat flow meter method [2], hot box-heat flow meter method [3], and quantitative infrared thermography [4]. All these methods are non-destructive, quantitative, and require the installation of temperature and/or heat flow sensors on both sides of the target wall. Qualitative methods based on visual inspection [5] exist as well, and diagnosing the presence or absence of insulation by drilling a hole from the exterior wall and inserting a borescope into the interior cavity is a method already commercially available.

Nagai et al. [6] proposed a probe insertion method that is applicable to a lightweight wall such as a timber frame structure in which a borescope and a temperature sensor are inserted through a tiny hole with a diameter of approximately 1 mm from the interior side to visually inspect and measure the temperature distribution of the wall. In addition to the simplicity of directly observing the inside of the wall with relatively minor damage, this method allows quantitative measurements such as heat transmittance even when it is difficult to measure the temperature outside the target area, such as a raised floor or a ceiling with an attic. In the temperature distribution measured by this method, the temperature sensor itself can be a thermal bridge, which causes a deviation from the original temperature distribution.
inside the insulation material. For this reason, it is necessary to define the specifications of a sensor suitable for the measurement; however, the physical parameters that affect the temperature deviation have not been fully understood.

This study aims to identify the parameters that determine the thermal bridge effect of a sensor probe inserted in insulation material, and to quantify the relationship between the sensor and insulation specifications and the deviation from the original temperature distribution inside the insulation material. First, we confirmed the thermal bridge effect by measuring the temperature distribution of an insulating material using two types of sensors with different diameters and thermal conductivities. Next, based on physical considerations, we introduced three dimensionless numbers that indicate the deviation of the measured temperature distribution. In addition, we confirmed by heat conduction simulation that the deviation is approximately the same if two out of the three dimensionless numbers are the same even if each parameter is different. Finally, using the dimensionless numbers, we suggest a procedure to determine the required specifications of a temperature sensor that can measure the temperature distribution accurately.

2. Experiment on thermal bridge of sensor probe

First, we confirmed the thermal bridge effect of the sensor probe by measuring the temperature distribution inside the insulation material using two types of temperature sensors. The insulation material shown in Table 1 was cut out to approximately 300 mm square, fitted into the opening of a constant temperature box, and a sensor was inserted in the insulation material from outside the box. For taking measurements, we initially set up a through-hole in the insulation with a diameter equal to the outer diameter of sensor 1. Subsequently, we inserted each sensor in the through-hole, and measured the temperature while sequentially setting the probes so that their temperature-sensitive area was at the depth shown in Table 1. At each depth, the sensor probe was held for a sufficiently long time to reach a steady-state condition.

Table 1. Experiment conditions.

| Insulation material | extruded polystyrene foam board with a thickness of 50 mm |
|---------------------|----------------------------------------------------------|
| Sensor 1             | Thermistor sensor housed in a SUS tube with an outer diameter of 0.9 mm and a needle-shaped tip |
| Sensor 2             | Thermistor sensor coated with nylon with an outer diameter of 0.7 mm |
| Temperature conditions | Insertion side: 20 °C Opposite side: 40 °C |
| Measurement depth    | 10 mm, 20 mm, 30 mm, and 40 mm from the surface of the insertion side |

Figure 1 shows the average of the temperatures measured four times for each depth and sensor. The horizontal axis represents the depth from the insulation surface of the insertion side, that is, the room side, normalized by the insulation thickness. The temperature was normalized so that the surface temperature on the insertion side was 0 and that on the opposite side was 1. The temperature inside the insulation, which is not affected by the sensor probe, is considered to have a linear temperature distribution shown by the dotted line, but the temperatures measured by the two sensors deviate from this expected temperature distribution and are affected by the lower temperature of the insertion side. In addition, the discrepancy is larger for sensor 1, which has a larger diameter and uses a material with higher thermal conductivity.
From these results, we can confirm the influence of the thermal bridge of the sensor probe, and that the deviation depends on the specifications of the sensor probe.

3. Derivation of dimensionless numbers affecting thermal bridge of sensor probes

3.1. Target of analysis and parameter normalization

To quantitatively analyze the thermal bridge effect of the sensor probe, we consider an insulation material with uniform thermal conductivity, hereinafter referred as specimen, and a sensor probe inserted in it, as shown in figure 2. In this study, we assumed steady-state conditions. The actual sensor probe consists of several different materials such as electrical leads, fillers, and outer coating, but we assume that the material is cylindrical with uniform thermal conductivity. We also assumed that the temperature measured by the sensor was the temperature at the tip of the sensor.

Under steady-state conditions, the nine independent variables listed in figure 2 determine the temperature distribution inside the specimen and the sensor probe. At the outset, we normalized the variables involved. The temperature, denoted by $\theta$, was normalized as mentioned above:

$$\theta^* = \frac{(\theta - \theta_{s,0})}{(\theta_{s,0} - \theta_{s,i})}$$

Here, the superscript ‘*’ denotes a normalized value. Similarly, length, $L$, is normalized by the specimen thickness, $D$, and the thermal conductivity, $\lambda$, by the thermal conductivity of the specimen, $\lambda_m$, that is,

$$L^* = \frac{L}{D}$$

$$\lambda^* = \frac{\lambda}{\lambda_m}$$

Because the unit of heat transfer coefficient, $\alpha$, is $[W/(m^2 \cdot K)]$, it can be normalized by $\lambda_m/D$ $[W/(m^2 \cdot K)]$, that is,

$$\alpha^* = \frac{\alpha}{(\lambda_m/D)}$$

In particular, the normalized $\alpha_m$, or $\alpha_m^*$, is

$$\alpha_m^* = \frac{\alpha_m}{(\lambda_m/D)} = B_1$$

Here, $B_1$ is the Biot number of the specimen and the surrounding air.

Figure 2. Target of analysis and associated parameters.

Considering that the heat conduction and heat transfer equations are valid regardless of the units of each variable, the normalized temperature measured by the sensor is determined by the five dimensionless parameters $\alpha_m^*$, $\phi_s^*$, $\lambda_s^*$, $\alpha_s^*$, and $x^*$. $\theta_1^*$ and $\theta_0^*$ are dependent variables. That is,

$$\theta_1^* = -1/B_1$$

$$\theta_0^* = 1 + 1/B_1$$
3.2. Introduction of dimensionless numbers

In the previous section, we showed that five parameters define the temperature measured by the sensor probe. In this section, we introduce three dominant dimensionless numbers, other than the depth of the sensor, based on physical considerations to account for the sensor temperature by an even smaller number of parameters. The normalized room temperature is determined by the Bi number as shown in Equation (6).

Figure 3(a) shows a schematic of the heat flow around a sensor inserted in an insulating material. The temperature at the tip of the sensor probe, that is, the measured temperature, was determined by the temperature distribution of the sensor probe shown by the solid line. The temperature of the sensor probe exposed to room air converged to room temperature when it was sufficiently far away from the insulation. The distance from the insulation at which the temperature of the probe converges to room temperature depends on the ratio of the conduction heat flow \( q_a \) in the axial direction of the probe to the heat transfer \( q_a \) from the probe to the surrounding air. Therefore, we consider the conductance \( K_a \) in the axial direction of the probe and the conductance \( K_d \) from the probe to the ambient air, as shown on the left side of figure 3(b). Here, both the conductances are per reference length \( D \). In addition, when deriving the two conductances, the probe temperature was assumed to be uniform in the direction perpendicular to the sensor axis. We define the dimensionless number \( N_d \) based on the ratio of the two conductances, as shown in figure 3(b). The \( N_d \) value is regarded as a dimensionless number that primarily determines the temperature distribution of the probe in contact with the surrounding air.

\[
K_a \propto \frac{\lambda_s \phi_s^2}{\alpha_s D} \\
N_d \equiv \frac{K_a}{K_d} \equiv \frac{\lambda_s \phi_s^2}{\alpha_s} 
\]

\[
N_d \equiv \frac{K_a}{K_d} = \frac{\lambda_s \phi_s^2 \ln 2}{\phi_s} 
\]

In contrast, for the temperature distribution of the sensor probe inserted in the specimen, we introduce the conductance \( K_m \) between the sensor probe and the surrounding material, instead of the aforementioned \( K_a \). Consider a cylindrical region of material around the sensor, where the length is the reference length and the inner and outer diameters are the sensor diameter and twice the reference length, respectively, as shown on the right side of figure 3(b). If the temperature of the sensor probe is \( \theta_s \) and that of the outside of the cylinder is \( \theta_m \), the heat flow \( q_m \) from the probe to the surrounding region is as follows:

\[
q_m = 2\pi \lambda_m D \cdot \frac{\theta_s - \theta_m}{\ln(2D/\phi_s)} 
\]

Therefore, the conductance \( K_m \) is given by:

\[
K_m \propto \frac{\lambda_m \phi_s^2}{\ln(2D/\phi_s)} 
\]
We define the dimensionless number $N_c$ based on the ratio of the conductance $K_s$ of the sensor probe to the conductance $K_m$ mentioned above:

$$N_c \equiv \frac{K_s}{K_m} = \lambda_s^* \phi s^2 \ln \frac{z}{\phi_s^*}$$  \hspace{1cm} (10)

The $N_c$ value primarily determines the temperature distribution of the probe inserted in the insulation. In summary, the three dimensionless numbers $B_i$, $N_d$, and $N_c$ are expected to determine the deviation between the temperature measured by the sensor and the expected temperature inside the insulation.

4. Effect of sensor specifications on thermal bridge effect

4.1. Outline of simulation

To study the effect of the three aforementioned dimensionless numbers on the thermal bridge, an FEM-based heat transfer simulation was performed for an axisymmetric body, as shown in figure 4. Boundaries marked $\alpha_s$ or $\alpha_m$ are heat transfer boundaries, and those not marked are adiabatic boundaries. For the heat transfer boundaries, $\theta_i$ and $\theta_o$ were set to 0 °C and 100 °C, respectively, and the resulting temperature was normalized and presented using equation (1). Simulations were performed for all combinations of parameters in Table 2(a), and the computational parameters were set as shown in Table 2(b), applying the parameter normalization described in Section 3.

4.2. Outline of the simulation results

Figure 5 shows the temperature distribution of the sensor probe for different combinations of $B_i$ and $N_c$ values. In all cases, the temperature distributions were for the sensor inserted at a reference depth of 0.9. For both $B_i$ numbers, the smaller the $N_c$ value, the smaller the deviation between the temperature at the tip of the sensor, that is, the measured temperature and the expected temperature of the insulation at the same depth. Hereinafter, the difference is referred to as the normalized temperature deviation. The temperature distribution of the sensor probe in contact with the air differs among the six cases, but the differences other than the $N_c$ value do not appear to have a significant effect on the temperature of the sensor tip for a depth of 0.9.

4.3. The effect of dimensionless parameters on the normalized temperature deviation

Figure 6 shows the normalized temperature deviation at the tip of the sensor for each depth. Because the same combination of $B_i$ number and $N_c$ value was calculated for 16 cases with different $\phi_s^*$ and $\alpha_s^*$, their variations are shown in the boxplots. As seen in the previous section, the smaller the $N_c$ value, the smaller the normalized temperature deviation is. For $N_c=0.05$, the deviation becomes larger when the...
sensor is placed at a shallow depth, whereas for $N_c=1$, the deviation tends to increase as the sensor is inserted deeper.

![Figure 5. Temperature distribution of sensor probe whose depth is 0.9.](image)

According to figure 6, $N_c=1$ not only results in a larger normalized temperature deviation, but also in a larger temperature variation, even for the same Bi number and depth. Figure 7 compares the temperature distributions of the sensor probes for the cases in which the temperature at the tip of the sensor is the lowest and the highest for the same conditions of $B_i=3.5$, $N_c=1$, and $x^*=0.5$. Because a small Bi number results in a large difference between the indoor surface temperature of the wall and the room temperature, the difference in the temperature distribution of the sensor probe is considered to be larger depending on the $N_d$ value, especially when the sensor probe is set at a shallow depth.

![Figure 6. The effect of dimensionless parameters on normalized temperature deviation.](image)

Figure 8 shows the variation in the normalized temperature deviation for each combination of Bi and $N_c$ values. These variations were evaluated in the inter-quartile range, ignoring the differences in depth for all cases and excluding the depth of 0.1. In the case of $B_i \geq 3.5$ and $N_c \leq 1$, the difference in $N_d$ values and other factors is approximately within 0.05, in the inter-quartile range. Therefore, in the following section, we assume that $B_i \geq 3.5$ and $N_c \leq 1$, and that the temperature measured by the sensor is approximately determined by the Bi number and $N_c$ value.
4.4. Chart of normalized temperature deviation and its application.

Based on the above results, we prepared charts to illustrate the normalized temperature deviation for a specific number of Bi and \( N_c \) values, assuming that the influence of \( N_d \) and other factors can be ignored. Figure 9 shows the charts for \( B_i=6 \) and \( B_i=10 \). These charts were created with \( \phi_s^*=0.02 \), and \( \alpha_s^*=100 \). For the chart with \( B_i=6 \), the measurement results for the two sensors shown in Section 2 are also shown. The Bi number for the actual measurement was approximately 6–7. The \( N_c \) value varies depending on the depth of the sensor. As shown in the previous section, errors due to the \( N_d \) value can be involved when the sensor is shallow. In addition, considering the possibility that the heat from the finger supporting the sensor was transferred along the sensor probe, it is desirable to compare the measured value at deep positions of the sensor with the contour of the chart. With this consideration, it can be observed that \( N_c \) is approximately 0.7 for sensor 1 and \( N_c \approx 0.4 \) for sensor 2. Note that the \( N_c \) values depend on the properties of the insulation material as well as the sensor probe.

If we measure the temperature distribution as the procedure described in Section 1 with a particular sensor inserted in an insulation material of a known thickness and thermal conductivity, then, we can determine the \( \lambda_s \), hereafter, the equivalent thermal conductivity, of the sensor using equation (10) based on \( \phi_s \) of the sensor and the \( N_c \) value read from the chart. In other words,

\[
\lambda_s = \frac{N_c}{\phi_s^2 \ln(2/\phi_s^2)} \cdot \lambda_m = \frac{N_c}{\phi_s^2 \ln(2D/\phi_s)} \cdot \lambda_m
\]  

(11)

For example, we obtain \( \lambda_s=15.6 \) W/(m·K) and 14.0W/(m·K) for the sensors 1 and 2, respectively, because the thickness of the polystyrene foam board is \( D=0.05 \)m and the thermal conductivity is \( \lambda_m=0.034 \) W/(m·K).

Once the equivalent thermal conductivity of the sensor is known, it is possible to estimate the reliability of the temperature measured by the sensor when applied to another insulation material. In other words, by measuring the thickness of the insulation material using a borescope and applying the assumed value of thermal conductivity of the insulation material, the \( N_c \) value for the combination of the sensor and the wall to be measured can be estimated using Equation (10). For example, when applying sensor 1 for a 100 mm thick foam insulation, assuming that the thermal conductivity is \( \lambda_m=0.03 \) W/(m·K), we can estimate \( N_c=0.23 \), which results in a standardized temperature deviation of about −0.15 to −0.10, according to the chart.

In this way, the chart of normalized temperature deviations organized by Bi number and \( N_c \) value, as shown in figure 9, provides a specification of the sensors that can measure the temperature distribution inside the insulation material or can be used to evaluate the reliability of the measurement results.
5. Conclusions
In this study, we focused on the thermal bridge effect that occurs when a sensor probe is inserted in a wall to measure the temperature inside the insulation material. Based on physical considerations and heat conduction simulation, we introduced two dominant dimensionless numbers that determine the deviation between the temperature measured by the sensor probe and the original temperature distribution inside the insulation material. The two dimensionless numbers studied were the Biot number and the newly defined $N_c$. The new $N_c$ number represents the ratio of the heat conductance of the sensor probe in the axial direction to that from the probe to the surrounding insulating material. In addition, we introduced schematic charts for determining the temperature deviation, to establish the required specifications of a suitable temperature sensor, or to evaluate the reliability of the measurement results. The issues to be addressed in the future include the confirmation of the similarity law using actual sensor probes and applying the proposed chart to the correction of the measurement results. The effect of the air gap between the probe and the insulation material and the deformation of the insulation when the sensor is inserted need to be clarified for practical applications.

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