MODELING AND CALIBRATION OF LATERAL HEAT LOSS RATE IN MEASURING THE R VALUE OF PARTLY HEATED WALL

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ABSTRACT

An experimental apparatus (in-situ thermal test unit) and an analysis method have been developed for evaluating the thermal resistance of the building envelope on site. This system estimates the thermal resistance of a wall by heating the outside wall surface and measuring the surface heat fluxes and temperatures on both sides of the wall. The heating panel is attached to the outside surface to avoid the effect of outside weather and to keep the surface temperature constant. The inevitable problem of this kind of testing method is, however, the error caused by the lateral heat loss. The error rate increases as the thickness of the envelope increases.

In this study, a calibration method has been developed that is able to compensate for lateral heat loss. The calibration model was made up through simulation using 3-dimensional heat flow calculation program (Voltra , Physibel). To validate this method, an experiment was conducted on mock-up blocks composed of insulation and bricks. The In-Situ measurement system adopting this calibration model could be expected to get more reliable results in evaluating thermal conductance on site.

INTRODUCTION

Because of the occurrence of considerable heat exchange with the external environment in the envelope of buildings, the total energy consumption of a building depends on the thermal performance of the facade, floor and roof.

The thermal conductance- designed prior to construction is subject to vary and deteriorate in quality due to construction irregularities, multi-dimensional heat flows, degradation effects and so on. Therefore, the measurement method of U-value in the field is required for post-evaluation of thermal performance of envelopes.

Since the 1980's, there have been several attempts at the in-situ measurement of U-value. Among them, the Envelope Thermal Testing Unit (ETTU) by LBL (Lawrence Berkeley Laboratory, U.S.A., 1985) and mathematical analysis methods like the dynamic method (C.Lout, 1985) are noticeable. According to the result of the experiment conducted by LBL, there were considerable divergences, particularly in heavy weight walls such as concrete, between the measured U-value and the real value. By analysis, it was shown that this error was caused by lateral heat loss in the wall, which accounted for about 50 % of the supplied heat flow.

In the case of mathematical analysis methods using a heat flow meter and surface temperature, even though the dynamic analysis method can make measurement time shorter than other methods, the duration of measurement for a reliable result is still too long. For example, it is recommended in ISO 9869 that more than 72 hours measurement time shall be required in the case of heavyweight constructs. If the condition around the measured area is unstable and irregular, the duration should be longer otherwise results are unacceptable.

In this study, a calibration method has been developed that is able to compensate for lateral heat loss. The calibration model was made up through the simulation of thermal behavior of internal wall surface temperature by a 3-dimensional heat flow calculation program (Voltra, Physibel). In order to validate this method, experiments were conducted on mock-up blocks composed of insulation and bricks.

THE CHARACTERISTICS OF SURFACE TEMPERATURE PROFILE ON THE PARTLY HEATED ENVELOPE

The characteristics of the surface temperature profile on the partly heated envelope, which was obtained through experiment, and computer simulation work is as follows.

a) Even though the overall thermal resistance of composite wall with identical materials is the same, the lateral heat loss rate varies depending on the order of the layers. Figure 1 and Figure 2 show that even though the U value of wall is identical, the shape of curve representing temperature profile differs depending on the insulation position. This phenomena is considered to occur because the structure of layers in the construction affects the lateral heat conduction.

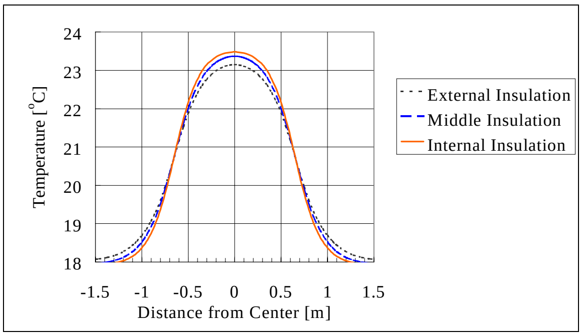

Figure 1. Temperature profile variations of inside wall surface with same thermal resistance depending on the insulation position

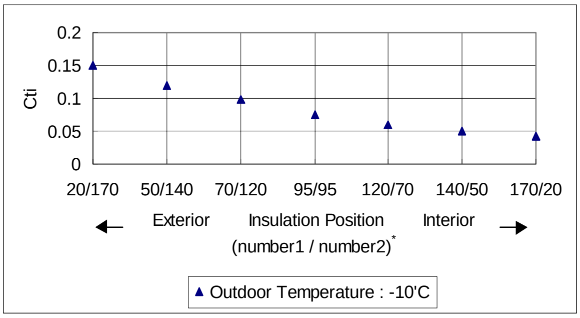

Figure 2. The example of the heat loss rate for the wall with same thermal resistance depending on the insulation position

Where, number1 : Exterior Thickness [mm]

/ : Insulation [50mm]

number2 : Interior Thickness [mm]

b) The decrease in heat flux on the opposite surface to the heated area is determined by the thermal properties (conductance, thickness and so on) and the condition of surrounding temperatures. (figure 3)

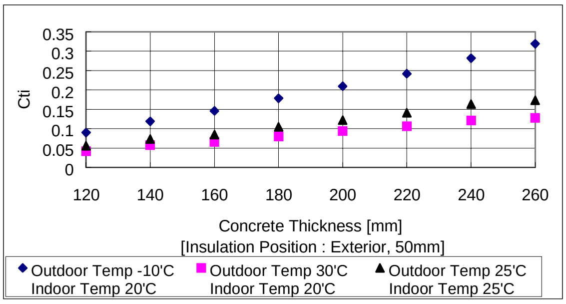

Figure 3. The example of the heat loss rate for thermal resistance depending on the thickness of envelope and surrounding temperature

c) The profile of the dimensionless temperature rates on the opposite surface to the heated area is identical in the same structure regardless of the condition of surrounding temperature (figure 4. and figure 5.). Here, the dimensionless temperature rate, which has the value from 0 to 1, is defined as follows.

$$tx = \frac{Tx - Ti\,min}{Tc - Ti\,min} \qquad (1)$$

Where

tx : dimensionless temperature rate on x position.

Tx : surface temperature on x position in the opposite side to heated area (K)

Tc : surface temperature at the center of the opposite side to heated area (K)

Timin : surface temperature at the position not affected by heated area (K), theoretically the farthest away from the center

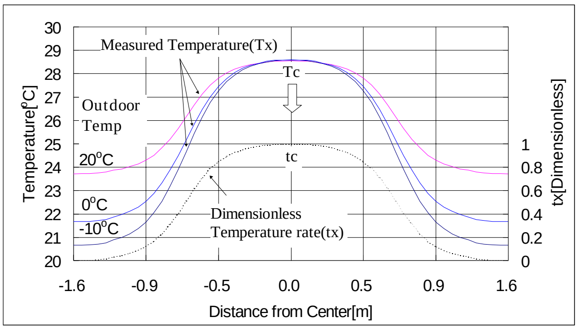

Figure 4. Surface temperature profiles of the inside wall surface to the heated area depending on surrounding temperatures

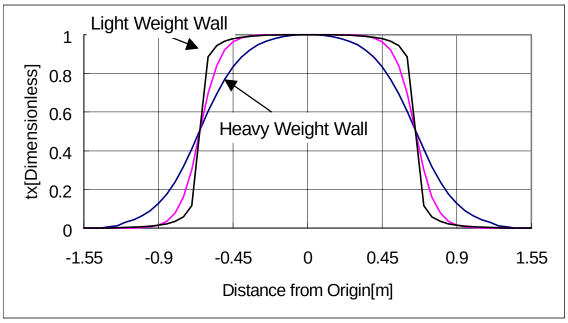

Figure 5. The example of the dimensionless temperature rate of the various walls

PRINCIPLE AND METHOD

1. Definition of lateral heat loss rate, Cti

The lateral heat loss rate (Cti) is defined as

$$Cti = \frac{Qp}{Qs + Q2} = \frac{ai(T'c - Tc)}{ai(Tc - TI)} = \frac{T'c - Tc}{Tc - TI} \qquad (2)$$

Where, ai is the heat transfer coefficient on inside surface (W/m^2K), T'c is the surface temperature on the center of inside in ideal condition (K), Tc is the surface temperature on the center of inside in partly heating condition (K), and Tl is indoor air temperature (K). (Figure 6)

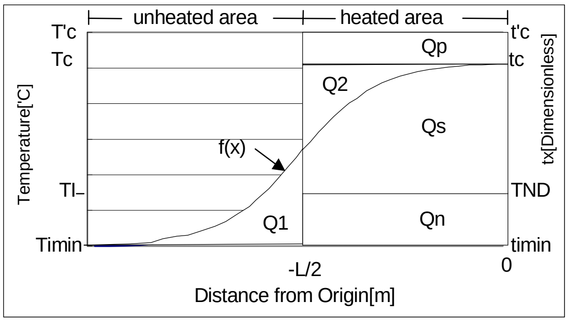

Figure 6. The concept of lateral heat loss around the border between the surface heated and the surface unheated.

* Here, -L/2 in the figure is the position of the border between surface heated and surface unheated, and L is the length of heating plate

The lateral heat loss ratio (Cti) caused by partly heating can be written in terms of the following relation

$$\begin{aligned} Cti &= \frac{T'c - Tc}{Tc - Ti\min} \times \frac{Tc - Ti\min}{Tc - TI} \\ &= \frac{T'c - Tc}{Tc - Ti\min} \times \frac{1}{1 - TND} \end{aligned} \qquad (3)$$

Where TND is (Tl - Timin)/(Tc - Timin) which expresses the dimensionless temperature rate between indoor air temperature and the inside surface temperature. The lateral heat loss ratio (Ctib), which is in the case of TND=0, can be defined as follows.

$$Ctib = \frac{T'c - Tc}{Tc - Ti\min} \qquad (4)$$

Therefore, equation (3) implies that the lateral heat loss ratio (Cti) depends on both of the basic heat loss ratio (Ctib) and TND determined by the condition of the surrounding temperatures.

2. Modeling for the profile of the dimensionless temperature rates on inside surface

The measurement points on site would not be continuous. In order to overcome the limited number of measurement points, a curve-fitting method was adopted to make the model, which should be able to represent the profile of the dimensionless temperature rates on inside surface. The model for curve-fitting adopted in this study is as follows.

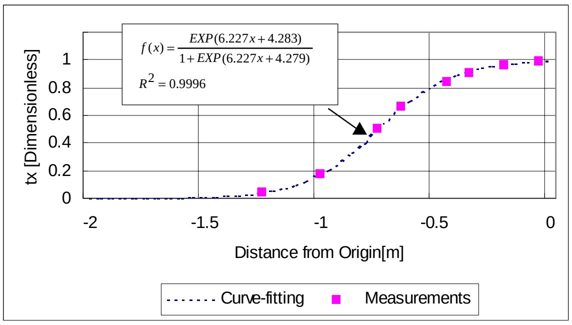

Figure 7. An example of curve-fitting the profile of the dimensionless temperature rates from center to edge (137cm x 137cm partly heated)

$$f(x) = \frac{e^{ax+c}}{1 + e^{ax+b}} \qquad (5)$$

3. Calibration method

The calibration concept is based on the idea that the shape of the curve representing dimensionless temperature profile on inside surface is affected by the lateral loss rate of the envelope. After several trial of making a variable that could explain lateral heat loss, we found that Ye defined in equation 6 has a reliable correlation with the basic lateral heat loss rate (Ctib).

$$Ye = f(-L/2) - 0.5 \qquad (6)$$

Where L is the total length of heating plate, and -L/2 means the end point of heating area.

Accordingly, it can be made to extract the correlative equation between the lateral heat loss rate (Ctib) and the Ye that could determine the error rate of the tested wall.

For example, in the case of $Ye \leq 0$ when $f(-L/2) \leq 0.5$, the lateral heat loss does not affect the drcrease of center temperature. And the value f(-L/2) increases above 0.5 as the lateral heat loss increases. Being based on the correlation, the curve for calibration can be made.

4. Simulation and calibration curve

A simulation was carried out to get the curve which represents the correlation between Ye and Ctib. About 60 kinds of envelope structure were set up for the simulation, which included RC, PC, brick, etc and ranged in 0.18 ~ 0.37 (m) in terms of thickness, in 0.34 ~ 2.57 (m^2K/W) in terms of thermal resistance. It was assumed that the structures are heated partly on outside with a 137 cm x 137 cm heating panel.

Combining the curve of correlation between Ye and Ctib extracted from the simulation with TND, the calibration curve with dependence parameter Cti can be written as follows.

$$Cti = Ctib \times [1 / (1-TND)]$$
$$= [2.0976Ye + 49.5885\ Ye^2] \times [1/(1-TND)] \quad (7)$$

Figure 8 shows the variation of TND depending on indoor and outdoor temperature. Figure 9 shows the relationship between Ctib and Ye. And Figure 10 shows the relationship between R-correction value and Cti that is obtained from equation 7. R-correction value means the value to be used for calibrating the R-value with lateral heat loss when the wall is heated partly. The equation for R-correction value is as follows.

$$\text{R-correction value} = -0.81949 \times Cti + 0.988185 \quad (8)$$

As it is shown in Figure 10, it can be suggested that the curve should be able to calibrate the error caused by lateral heat loss. The final equation to calibrate the R-value is as follows

$$R' = R \times \text{R-correction value} \quad (9)$$

Where

R' : Calibrated thermal resistance of tested wall

R : thermal resistance of tested wall with lateral heat loss when the wall is heated partly

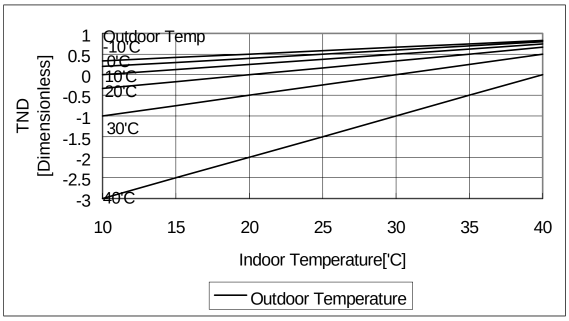

Figure 8. Example of dimensionless temperature TND depending on indoor and outdoor temperature when heating temperature is 50°C

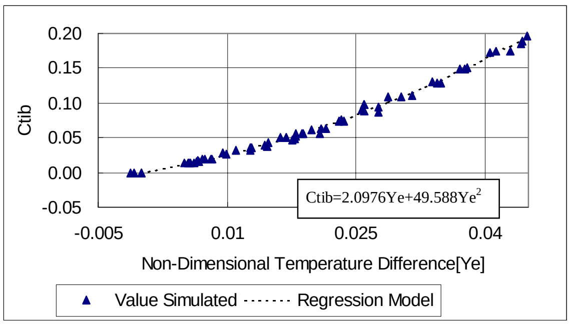

Figure 9. Relationship between Ctib and Ye

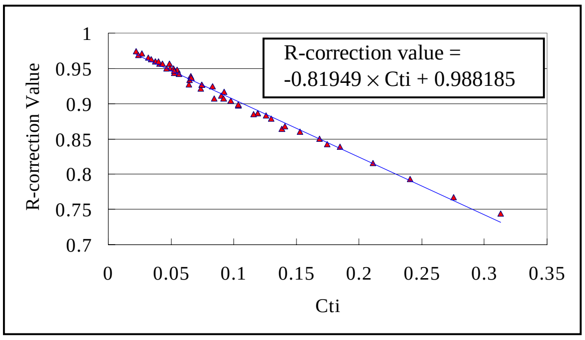

Figure 10. Relationship between R-correction value and Cti

EXPERIMENT AND VALIDATION

1. Heating plate and measurement system

A heating plate (137cm(W) x 137cm(H) x 4cm(D)) was developed which is attached to the outside wall and which provides constant heat energy to make quasi-steady condition in the area (Figure 11). In order to enhance control accuracy, the heating area is divided into interior zone and perimeter. The perimeter zone consists of four sub zones. The interior zone also has one sub zone (60 cm x 60 cm) in the middle of it and 4 sub zones around the middle

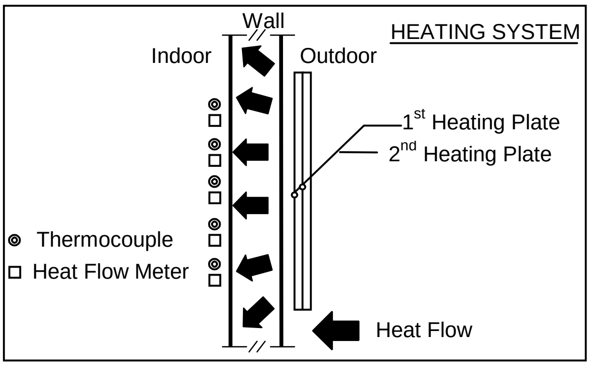

Figure 11. The scheme of heating plate and measurement system

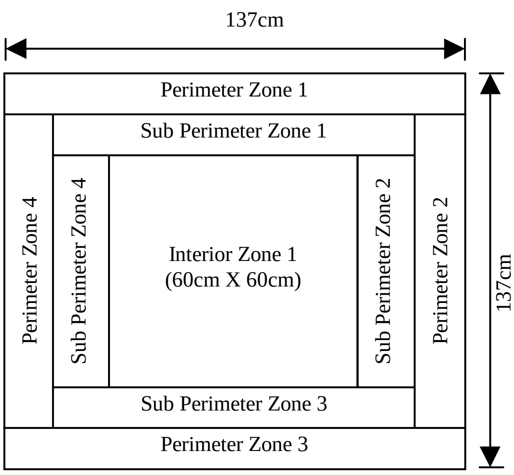

Figure 12. The control zone of heating plate

sub zone. There are, therefore, 9 sub zones in the plates which are each controlled by its own circuit controller. (Figure 12)

Heat flow meters and thermocouples were adhered to the surface of both sides of the wall to measure surface temperature and heat flux. The data were stored automatically using a portable data logger and a personal computer.

In addition, an infrared camera was used to detect the thermal distribution on the inside surface so that the position of heating panel could be found.

2. Mock-up Envelope

A mock-up model was made up as an object to validate the calibration method theoretically established with computer simulation. The mock-up is composed of mortar (15mm), cement brick (190mm), insulation (50 mm) and plasterboard (9mm). The thermal conductivity of each element is shown in table 1.which was obtained through thermal conductivity test with Rapid-K and QTM method.

According to the data in table 1., the overall thermal resistance of the mock-up is 1.512(m^2K/W). This was used as a reference value to compare with the result from measurement and calibration.

Figure 13. The scene of experiment

3. Result

The surface heat flux stabled at an average 20.09 W/m^2 after about 27 hours passed since heating wall outside. According to heat flux and surface temperature, the thermal resistance of the mock-up was calculated as an average value of 1.572 m^2K/W (1.561~ 1.583 m^2K/W) after the heat flow stabled.

Applying TND and Ye obtained from measured data to the equation 7, we can get a Cti 0.0381. And applying Cti to the equation 8, R-correction value is obtained. The thermal resistance is finally calibrated with R-correction value. The calibrated result is 1.514 (m^2K/W) which coincides with the reference value (1.512 m^2K/W). (Table 3)

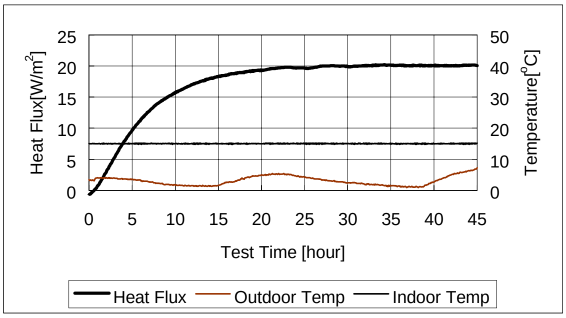

Figure 14. Heat flux and temperature on the surface of the middle zone (60cm x 60cm) in inside

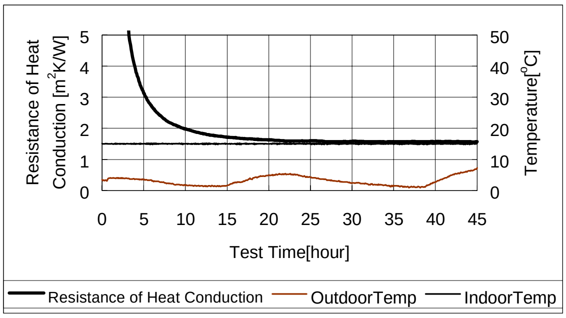

Figure 15. Heat resistance from measurement

Table 1. Thermal conductivity of test wall materials

Material	Thermal conductivity (W/mK)
Mortar	1.4236
Cement brick	1.3557
Insulation	0.03807
Plaster board	0.241

Table 2. The result of measurement

Item	The result of measurement
Room air temp. (K)	15.01
Outdoor temp (K)	3.02
Inside wall Surface temperature	17.55
Heated wall Surface temperature (K)	49.13
Heat flux (W/m^2)	20.09
Thermal resistance (m^2K/W)	1.572

Table 3. Comparison of thermal resistance values

Item	Thermal resistance (m^2K/W)	R-correction Value
Theoretically result	1.512	-
Test result	1.572	0.9631
Calibration result	1.572 x 0.9631 = 1.514	

CONCLUSIONS

In order to overcome the limitation of In-Situ measurement when using a partly heating panel system, a calibration method was suggested which was based on computer simulation, curve-fitting and a regression method.

Important results are as follows.

1. The profile of the dimensionless temperature rates on the opposite surface of heated area is unique in the same structure even though the real temperature profile of the surface temperatures varis depending on the condition of surrounding temperatures.

2. The reliable curve for calibration can be obtained from computer simulation, curve-fitting model and nonlinear regression. It can be expected that the more simulation cases and the more the data is accurately measured for curve-fitting model, the better the calibration curve is.

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NOMENCLATURE

T'c : the surface temperature on the center of inside in ideal condition with no lateral heat loss (K)

Tl : indoor air temperature (K)

x : the distance from the center in the opposite side to heated area(m)

ai : the heat transfer coefficient on inside surface (W/m^2K)

Cti : the lateral heat loss rate affected by partly heating

Ctib : the lateral heat loss rate affected by thermal property of wall

TND : dimensionless temperature of indoor temperature

a, b : constants obtained by curve-fitting.

t′c : dimensionless temperature of T′c

tc : dimensionless temperature of Tc

timin : dimensionless temperature of Timin