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Comparative study of Hot Box Test Method using laboratory evaluation of thermal properties of a given building envelope system type

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ABSTRACT

This research mainly focuses on the experimental setup of the Hot Box Test Method and comparison of different models for measurement of thermal properties of building envelope systems. Hot Box Test Method has long been used to determine the thermal properties of building envelope systems, however, the steady-state assumption for calculation is not always desired, especially when the environmental conditions cannot be controlled. To utilize models considering the dynamic behavior of buildings for in-situ measurement, it is desired to first validate such models and compare the performances with hot box test. Therefore, the performances of several dynamic models, including Anderlind's Regression Model and R-C Network Model, have been studied. Hot box tests were performed in the Building Enclosure Testing Laboratory (BETL) at Penn State University and the results show the 3R2C model turns out to be the most accurate one among the dynamic models explored in this study. With a temperature difference larger than 20 °C, all dynamic models are validated with a percentage difference lower than 7% compared with the steady-state analysis, giving us alternatives for R-value measurement when in-situ measurement condition are applied.

1. Introduction

The thermal properties of building envelope (BE) systems can significantly influence the overall energy performance of buildings, and thus accurate determination of such properties is needed. Hot Box Test Method has been used as a reliable method for measurement of thermal properties of building materials and envelope assemblies in the U.S. for decades, starting with Mumaw [1]. ASTM C1363 standard provides guidelines for the use of hot box test in the U.S. [16]. This paper starts by discussing a review of the Hot Box Test Method, and then focuses on the experimental setup in the Building Enclosure Testing Laboratory (BETL) at Penn State University, as well as the validation of several data analysis models considering both the steady-state and dynamic behavior of the specimen. The specimen that is described in detail in Section 3.2 is an opaque wall panel with nine different segments with dimensions of the center concrete masonry unit segment, which is the subject of measurement in this study, being 110 cm long * 70.1 cm high and with 38.1 mm thick fiberglass insulation and 9.5 mm thick paging.

2. Literature review

2.1. Hot Box Test Method

Based on Hot Box Test Method, a specimen is located between two chambers: the metering chamber and the climatic chamber. The metering chamber is used to simulate the interior environment (hot side), while the climatic chamber is used to simulate the exterior environment (cold side). Heating and cooling systems are used in the metering chamber and climate chamber, respectively, to create the temperature difference. The thermal resistance of the panel can then be evaluated by using the measured heat flow from the metering chamber side to the climate chamber side passing through the specimen, and the measured temperature difference between the hot and cold sides. This test procedure requires defining areas of specimen where homogeneous thermal properties and steady-state heat transfer can be assumed [2]. As can be observed in Fig. 1, the heat flow directly passing through the specimen equals the heat input required to keep the metering chamber at constant temperature subtracts the heat loss through

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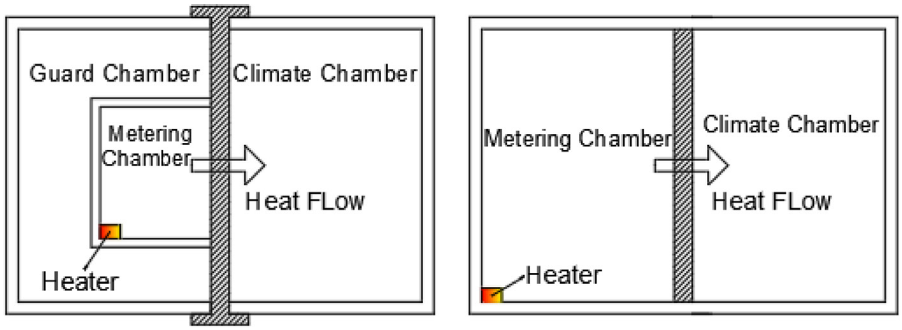

Fig. 1. Guarded hot box (Left) and Calibrated hot box (Right).

walls and surrounding panels. By maintaining the two chambers at constant temperatures, the steady-state condition can be reached.

There are two basic hot box setups: the "guarded hot box" that uses a metering chamber inside the "guard chamber", and the "calibrated hot box" that uses the surrounding environment as the "guard chamber". The guarded hot box is to keep the guard chamber and the metering chamber at the same temperature, thus the heat loss through metering box wall is not necessary to be determined [2]. The calibrated hot box, on the other hand, uses the outside environment as the "guard chamber", and by measuring the temperature difference between the surrounding environment outside of the chamber and the metering box, the heat loss through walls can be obtained. Both of these two setups need to have well-insulated interior. By making the assumption of steady-state condition, the 1-D heat transfer passing through the specimen can be expressed as:

$$q = \frac{1}{R_t}(T_{in} - T_{out}) \quad (1)$$

where R_t is the overall resistance of the wall specimen, including surface resistances R_{si} and R_{so}, T_{in} is the air temperature of hot (interior) chamber, and T_{out} the air temperature of cold (exterior) chamber. It should be noted that the specimen surface-to-surface resistance R_s can be expressed as:

$$q = \frac{1}{R_s}(T_{s,in} - T_{s,out}) \quad (2)$$

where $T_{s,\ in}$ is the interior surface temperature and $T_{s,\ out}$ is the exterior surface temperature. Generally, for engineering calculation of the overall R-value for building walls, it is appropriate to consider the total heat transferred from interior air to exterior air all by conduction, with two fictitious films considered at both sides of the wall to represent the effect of convection and radiation. The surface resistances for such air films (that is, the heat transfer coefficient between the specimen surface and the air) for both interior R_{si} and exterior R_{so} can be expressed as:

$$q = \frac{1}{R_{si}}(T_{in} - T_{s,in}) = \frac{1}{R_{so}}(T_{s,out} - T_{out}) \quad (3)$$

The parameters and variables used in above equations are defined as follows: q= heat flux, R_t= overall resistance, R_s=surface-surface resistance, R_{si}=interior heat transfer coefficient (film resistance), R_{so}=exterior heat transfer coefficient (film resistance), T_{in}=interior environmental temperature, T_{out}=exterior environmental temperature, $T_{s,\ in}$=interior surface temperature, $T_{s,\ out}$=exterior surface temperature.

It is clear that the equations above are based on steady-state assumption as the heat flux passing through each layer of the wall is assumed to be constant. The thermal resistance of the specimen R_s is the output of the hot box test and a very important coefficient for the commonly used building energy simulation tools such as BEopt, DesignBuilder, etc.

The Hot Box Test Method has been long used as a reliable tool for evaluation of thermal resistances of building elements. Some of the uses of the Hot Box Test Method by different authors are mentioned here to illustrate the broad applicability of the experimental approach. Burch et al. [3] studied a dynamic test method for determining transfer function coefficients for a wall specimen using a calibrated hot box. Fazio et al. [4] tested the hygrothermal performance of a large-scale envelope specimen by using Calibrated Hot Box Test Method. Fang [5] measured the U-factor for windows with a high-reflectivity venetian blind by using a two side-by-side hot box apparatus. Elmahdy et al. [6] studied the experimental procedure and uncertainty analysis of the Guarded Hot Box Test Method to determine the thermal transmission coefficient of skylights and sloped glazing. Wakili and Tanner [7] measured the U-factor of a dried wall made of perforated porous clay bricks by using a hot box test apparatus with a heat flow meter. Gao et al. [8] evaluated a reduced linear state model of hollow block walls and validated it by hot box test measurement. Wakili et al. [9] used a hot box test apparatus to measure the thermal transmittance of a balcony with integrated glass fiber reinforced polymer GFRP elements and compared the results with numerical analysis. Geoola et al. [10] tested the overall heat transfer coefficient for greenhouse cladding materials with and without thermal screens by using guarded hot box. Martin et al. [11] studied the effect of thermal bridge in walls though guarded hot box tests, which were designed and carried out both for steady-state to determine the R-value, and for dynamic state aimed at figuring out the amplitude and phase lag of internal heat flux. Kus et al. [12] tested a pumice aggregate concrete hollow block wall panel by means of Calibrated Hot Box Test Method. Kossecka and Kosny [13] discussed a simplified procedure for estimation of minimum time of a Hot Box Test for BE assemblies.

2.2. Dynamic calculation models

Even though it is appropriate to make steady-state assumption for Hot Box Test Method as we can maintain both the interior and exterior temperature at constant level in order to minimize the dynamic heat storage effect off the wall, it should be clear that an ideal steady-state condition is hard to be reached outside laboratory. Therefore, dynamic analysis is necessary for more accurate thermal property determination, especially when the exterior environmental condition keeps changing, as is the case for onsite measurement of the BE systems. Cesaratto and Carli [14] compared the results of using several methods for R-value calculation based on a number of in-situ tests and the corresponding influence on the net building energy demand. The results indicated that different methods lead to significant different results, up to 30% in the R-value. This then resulted in the net energy demand to vary between 11%–14%.