Cold-Soak Testing Method -Based Evaluation of Thermal Performance of A Typical Residential Dwelling

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ABSTRACT

Thermal characteristics of two identical British-style residential houses were evaluated and compared to each other in this paper. The two houses were built in Scotland under the Scottish building regulation 2011. Thermal characteristic evaluation of the houses was accomplished by determining their heat loss coefficient and thermal mass potential. A practical heating measurement method was applied to evaluate heat loss coefficient before a thermal mass storage evaluation was carried out using a cold soak testing method. This cold-soak testing method is based on evaluation approach under the absence of effect of solar radiation that eliminates solar heat gain during the assessment period. Because of this, the uncertainty of analytical result could be reduced and the accuracy of evaluation result would be improved. The evaluation result indicated that heat loss coefficient of the two identical houses was almost the same while their thermal mass storage potential was quite similar with a small difference of 5.5% that is thought to be caused by a different number of heating systems installed in each house as well as small differences in either variability in materials or variability in the batch of material that the houses were made.

1. INTRODUCTION

Understanding thermal characteristics of residential houses can help minimize heating or cooling load and improve efficiency of HVAC systems as well as optimization of their control system for energy savings. In most cases, evaluation of house thermal characteristics is usually to determine the amount of heat that leaks from house fabric and to estimate heat gain from solar radiation. Both heat loss and solar gain can be easily obtained by practical measurement methods that are commonly used in the UK including co-heating test and in-use heat balance test. However the practical measurement methods mentioned here are almost not able to evaluate the potential of house thermal mass storage which is also an important property of house thermal characteristics.

In this paper, the so-called cold-soak testing method is applied to quantify thermal mass storage potential of two identical British-style residential houses. The proposed approach is developed and evaluated based on the test condition of night-time period when the effect of solar radiation is absent. This means that solar heat gain received by the houses during day-time is not included in data analysis. Thus the accuracy of analysis results is thought to be more trusted because it is identified that the largest sources of measurement error in the practical measurement methods is solar heat gain.

2. DESCRIPTION OF EVALUATION FACITIY

The evaluation facility has been set-up in Scotland in the form of two highly instrumented test houses that are mirror-symmetrical and identical detached houses. The test houses were built to comply with Scottish Building Standards (S.B.S) regulations 2011, under the Domestic regulations 2011 section. The houses were also designed to be backward compatible to the S.B.S regulations 1991, 1985 etc. by removing insulation accordingly.

The design U-value of the house elements is shown in Figure 1 in comparison with the standard U-value as assigned in the S.B.S regulations 2011. It can be seen from Figure 1 that the design U-value of some house elements is slightly higher than the standard U-value. This is attributable to the presence of thermal bridges in the design U-value calculation that results in a higher heat transfer through the house elements. The air change rate was also designed in accordance with the British Standard BS EN 12831 with a design value of 1.71 ACH (air change rate per hour).

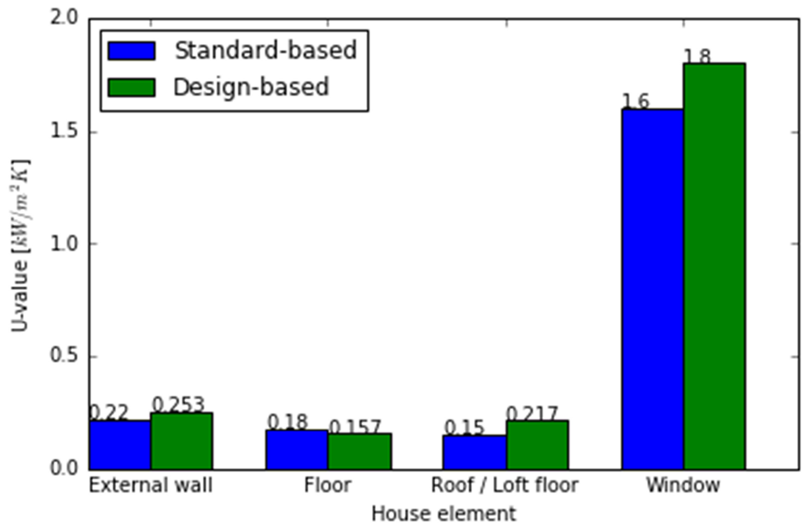

Figure 1: Standard and design U-value of house elements

There are about 1,500 sensors that were installed to measure the detailed indoor and outdoor environment conditions and in-depth monitor house performance as well as the operation of heating systems. The front view of the test houses in the evaluation facility can be seen in Figure 2. Each house consists of two stories with three bedrooms and one combined living and dining room which are main living spaces. Besides the main rooms, the houses also include smaller rooms such as kitchen, hall, bathroom, toilet etc. Number of rooms and floor plans are shown in Figure 3.

Figure 2: Mitsubishi Electric House-type Evaluation Facility

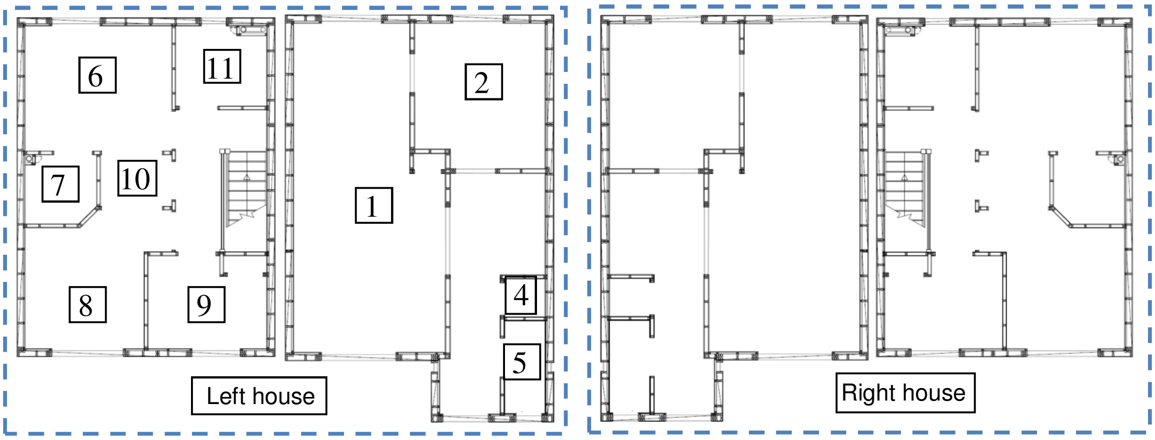

Figure 3: First-floor and ground-floor plans of test houses

Individual room volume is shown in the following table in comparison with whole house volume. Each room is assigned with its reference number including rooms 1-5 in ground floor and rooms 6-11 in first floor. Total area of ground- and first floors are 49.1 m^2 and 45.5m^2 respectively.

Table 1: Individual room volume in comparison with whole house volume

	Description	**Volume of room / volume of the house [%]**
Room 1	Living and dining room	29.5
Room 2	Kitchen	12.1
Room 3	Hallway and landing	11.0
Room 4	Shower	1.1
Room 5	Toilet	2.6
Room 6	Bedroom 1	12.9
Room 7	En-suite	3.5
Room 8	Bedroom 2	11.6
Room 9	Bedroom 3	7.8
Room 10	Utility room	2.6
Room 11	Bathroom	5.2

3. PROPOSED APPROACH

To evaluate thermal mass storage potential of the two houses by a cold-soak testing method, heat loss coefficient of whole house need to be determined. Assuming that the evaluation period is during night-time, amount of heat supplied from heat pump to heat the houses is equivalent to heat loss from indoor to outdoor. Thus whole-house heat loss coefficient is determined by the following equation:

$$\alpha = Q_{HP}/(T_h - T_a) \quad (1)$$

where,

$$Q_{HP} = \rho \times q \times C_p^w \times (T_{out}^w - T_{in}^w) \quad (2)$$

$$T_h = \sum(T_r \times V_r)/\sum V_r \quad (3)$$

where, T_r is the average temperature of each room in the house which is the mean of representative temperatures measured at many positions in the room and calculated as follows:

$$T_r = \frac{\sum T_i}{n}$$

After heat loss coefficient is obtained from a heating test using heat pumps, cold-soak test is applied to quantify apparent heat capacity of the houses for thermal mass evaluation. Based on this approach, test houses are isolated without heating for several days until trends of indoor temperature variation stabilize following the trends of outdoor temperature variation. Home appliances that are potential to dissipate heat to the houses such as computers, fridge, TV, lighting etc. must be switched off during the cold-soak test. Thermal mass storage of the houses is evaluated by the equation as follows:

$$C_r \left(\frac{dT_r}{dt}\right) = Q_s - Q_L \quad (4)$$

Due to the evaluation period of thermal mass storage that is also during nighttime from 11:00pm to 4:00am, solar heat gain Q_s is negligible while heat loss Q_L can be calculated based on whole-house heat loss coefficient from equation (1). Thus equation (4) becomes:

$$C_r \left(\frac{dT_r}{dt}\right) = -\alpha \left(T_h - T_a\right) \quad (5)$$

Based on equation (5), heat loss $-Q_L$ is plotted against hourly room temperature drop $\frac{dT_r}{dt}$ to give apparent heat capacity $\mathrm{C_r}$ as the gradient of the linear regression. Thus apparent heat capacity $\mathrm{C_r}$ can be obtained from the regression plot and representative for thermal mass storage of the house as follows:

$$C_r = -\alpha \left(T_h - T_a\right) \times \left(\frac{b}{c}\right) / \left(\frac{dT_r}{dt}\right) \quad (6)$$

where, b is a conversion factor from kW to kJ/h and c is a conversion factor from kJ to MJ.

4. EVALUATION RESULTS

4.1. Heat loss coefficient determination

For heating test to determine heat loss coefficient, both the left and right houses were heated by heat pumps. The house indoor were maintained at a stable high temperature while also taking the advantage of stable low temperature of the ambient in order to obtain a good condition of determining heat loss coefficient. Figure 4 shows a steady-state condition of indoor and outdoor temperatures and night-time periods at the winter time when heat loss coefficient was determined.

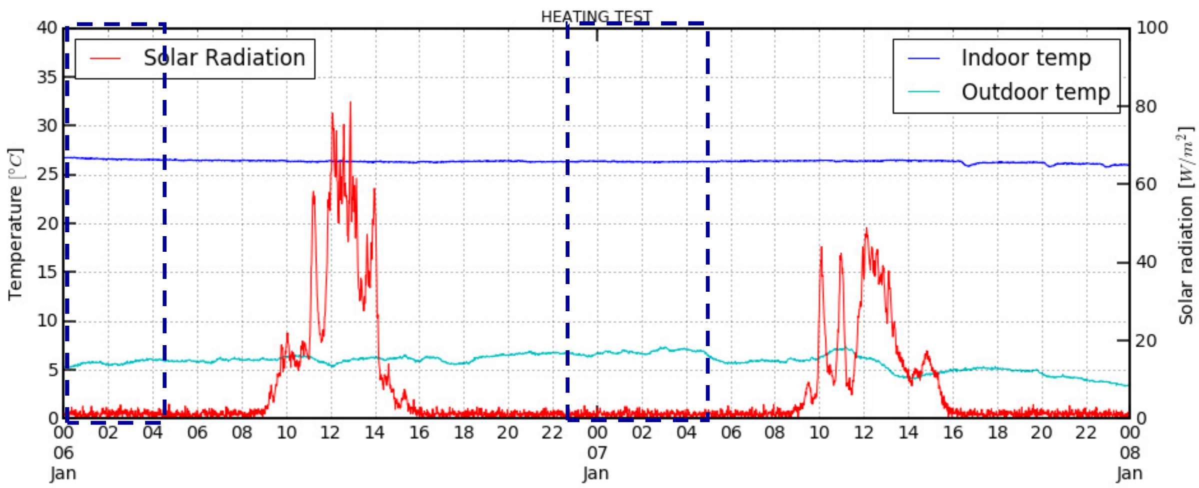

Figure 4: Data analysis period for whole-house heat loss coefficient (left house as a representative)

Due to the absence of solar gain during the night-time and no heat dissipation from home appliances, supplied heat produced by heat pumps is equivalent to heat loss of the whole house. As shown in Figures 5 and 6, heat loss coefficient is the gradient of the linear regression line in the plot that is forced through the origin due to the assumption of no supplied heat when the indoor and outdoor temperature difference is zero.

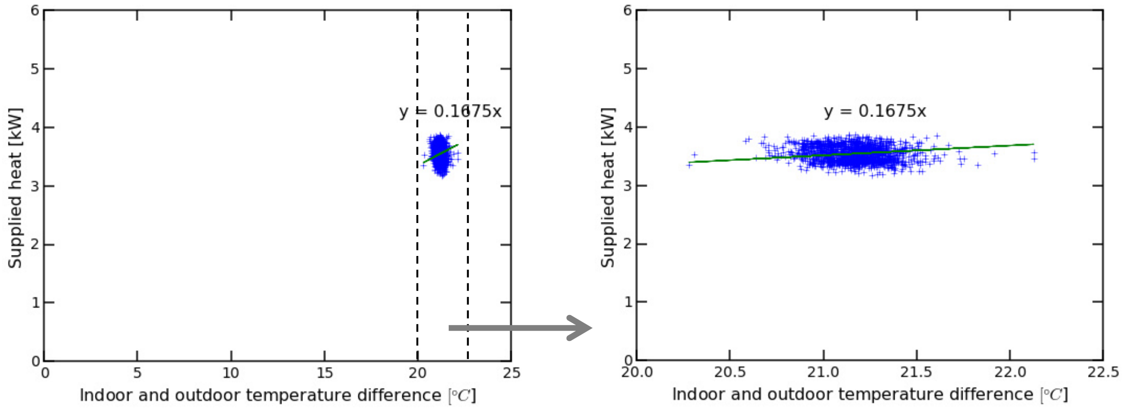

Figure 5: Regression plot for determining whole-house heat loss coefficient of left house

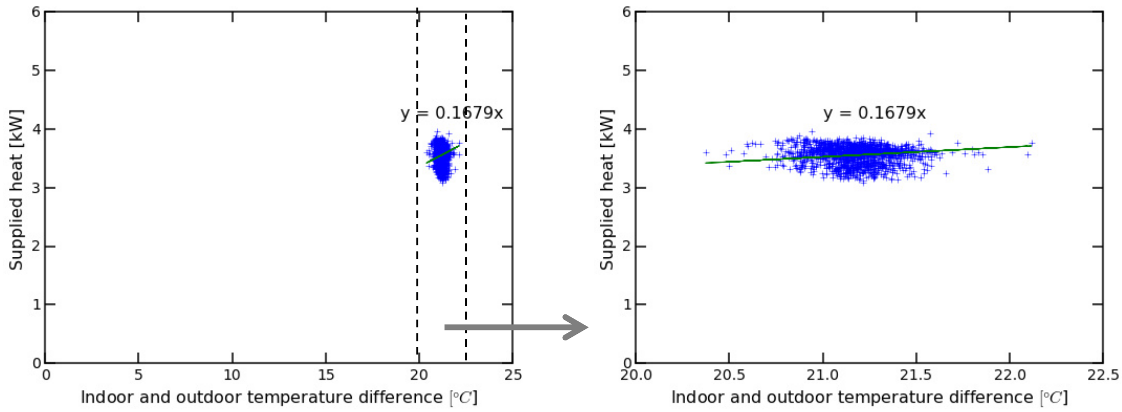

Figure 6: Regression plot for determining whole-house heat loss coefficient of right house

It can be seen from Figures 5 and 6 that heat loss coefficients of the left house ($\alpha = 0.1675$ kW/K) and of the right house ($\alpha = 0.1679$ kW/K) are almost identical. This is due to the same house design and architecture used for construction of the two test houses.

4.2. Thermal mass evaluation by cold-soak testing method

The cold-soak test was carried out for nearly ten days under non-heating condition in summer time from 01/07/2015 to 10/07/2015 when effect of solar radiation is seen to be significantly high. It took about 3 days from beginning of the test before indoor temperature variation reached a steady state together with steady-state variation of outdoor temperature and solar radiation.

The steady-state period for data analysis is highlighted in the dashed line as seen in Figure 7. It is a consecutive 5-day test period from 04/07/2015 to 09/07/2015 when the magnitude of indoor temperature fluctuation was quite similar throughout 5 testing days while the outdoor temperature fluctuation matched well with the variation of solar radiation.

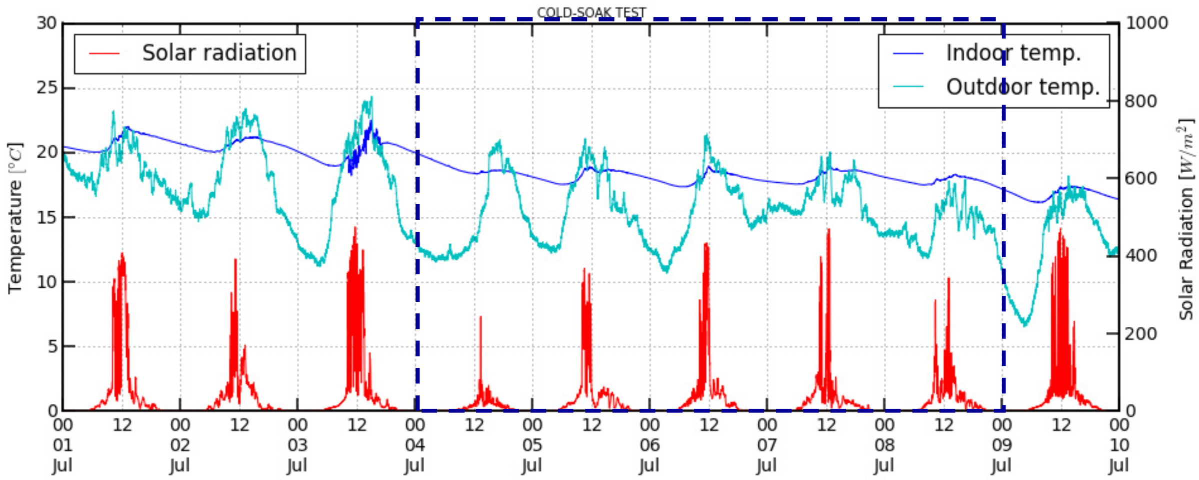

Figure 7: Evaluation period for thermal mass evaluation under cold-soak test (left house as a representative)

The evaluation period is taken with only night-time data from 11:00pm to 4:00am when solar radiation is absent. This means that the houses were being cooled down during the evaluation period due to heat loss from indoor to outdoor that causes indoor temperature to drop. Figure 8 shows the approach to quantify thermal mass storage of the two houses.

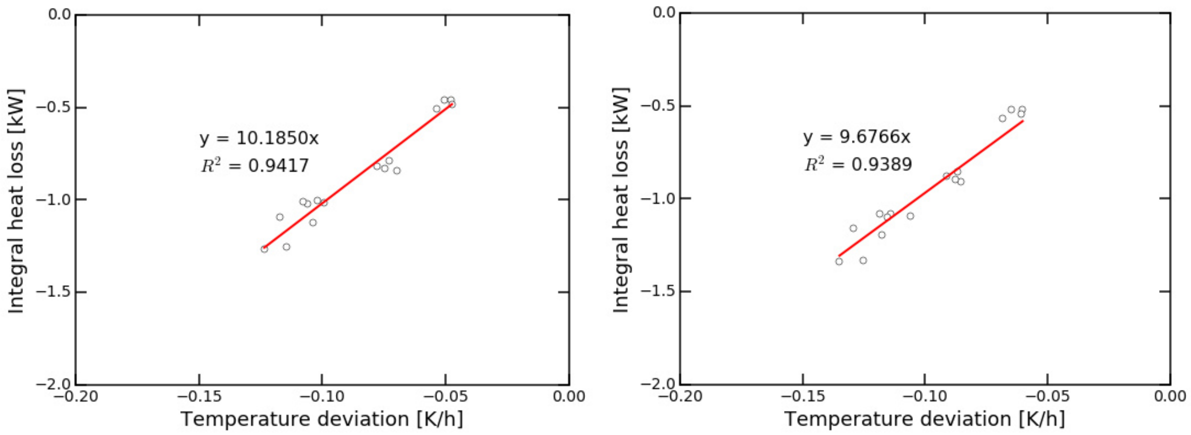

Figure 8: Regression plots for determining apparent heat capacity of left house (left plot) and right house (right plot)

Similar to the approach used for obtaining heat loss coefficient in Figures 5 and 6, if assuming no heat loss from house indoor to outdoor, room temperature has no drop. Thus the linear regression line must be passed through the origin (0, 0). By applying the equations (5) and (6), apparent heat capacity of the left and right houses is derived and summarized in table 2.

Table 2: Apparent heat capacity for thermal mass storage potential evaluation

	House	Apparent heat capacity [MJ/K]
1	Left	36.7
2	Right	34.8

Based on the analysis result of apparent heat capacity as shown in table 2, thermal mass storage is seen to be quite similar between the two houses with a small difference of 5.5%. This would be caused by a larger number of heating systems installed in the left house compared to the right house as well as small differences in either variability in materials or variability in the batch of material that the houses were made.

4. CONCLUSIONS

Thermal characteristics of two identical British-style residential houses in Mitsubishi Electric House-type Evaluation Facility are analysed and compared to each other. Thermal characteristic evaluation was accomplished by determining heat loss coefficient from a steady-state heating test and thermal mass storage potential from a cold-soak test. Due to the evaluation period of heat loss coefficient and thermal mass storage that was night-time when solar radiation was negligible, solar gain was not included in data analysis. Because of this, measurement error of solar radiation was eliminated from analysis results. The uncertainty of analytical result could be reduced and the accuracy of evaluation result would be improved. Comparing the evaluation results between the two houses, the heat loss coefficients were almost the same while thermal mass storage potential were quite similar with only a small difference of 5.5%.

NOMENCLATURE

Symbols

C_r	Apparent heat capacity [MJ/K]
C_p	specific heat capacity [kJ/kg^{o}C]
Q	heat capacity [kW]
t	time [hour]
T	temperature [^{o}C]
U	heat transfer coefficient [W/m^{2}K]
V	volume of room [m^3]
a, b	conversion factors

Subscripts

a	ambient
i	position for room temperature measurement
in	inlet
L	heat loss
h	house
HP	heat pump
out	outlet
S	solar
r	room

Greek

α	heat loss coefficient [kW/K]
ρ	water density [kg/m^3]

Superscripts

w	water

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