Error Analysis of QUB Method in Non-Ideal Conditions during the Experiment

Naveed Ahmad, Christian Ghiaus, Moomal Qureshi

Article

Error analysis of QUB method in non-ideal conditions during the experiment

Naveed Ahmad, Christian Ghiaus*, Moomal Qureshi

Univ Lyon, CNRS, INSA-Lyon, Université Claude Bernard Lyon 1, CETHIL, UMR5008, F-69621, Villeurbanne, France

* Correspondence: chrsitan.ghiaus@insa-lyon.fr

Received: date; Accepted: date; Published: date

Abstract: QUB is a short-term method for measuring the overall heat transfer coefficient of houses. The test involves heating and cooling the house with a power step and measuring the indoor temperature response in a single night. Ideally, the outdoor temperature during QUB experiment should remain constant. To compare the influence of variable outdoor temperature, the QUB experiments are simulated on a well calibrated model with real weather conditions. The experiments at varying outdoor temperature and constant outdoor temperature during the night show that the results in both conditions are nearly similar. A ± 20 % increase or decrease in the outdoor temperature during the QUB experiment can change the results in the measured overall heat transfer coefficient by ± 5 %. QUB experiments simulated during the months of winter show that the majority of results are ± 15 % of the steady state overall heat transfer coefficient. The QUB results during the months of summer show relatively large variation. The large errors coincide with the small temperature difference between indoor and outdoor temperature before the start of QUB experiment. The median error of multiple QUB experiments during summer can be reduced by increasing the set point temperature before the start of QUB experiment.

Keywords: overall heat transfer coefficient; building energy modelling; short term thermal characterization methods; energy efficiency.

1. Introduction

Significant savings can be achieved in both new and existing buildings. Depending on the level and type of retrofit (deep or shallow) and the type of building, the potential savings can range from 25 % to 90 % [1]. Due to this potential, building energy efficiency sector received highest percentage (58 %) of investments in energy efficiency sector in IEA member countries (including six major emerging economies Brazil, China, India, Indonesia, Russian Federation and Mexico) in 2017 [2].

Energy efficiency improvements require investments that are justified against the predicted savings. The saving predictions are based on simulation of annual energy consumption. The difference between estimation and measurement is usually referred as 'Performance Gap' [3]. Some of the reasons of performance gap are deterioration of building thermal properties, reduction in efficiency of equipment, operation off the designed values, changing weather pattern, changes in operation schedule, occupancy and inability of simulation tools to cover complete dynamics of building [4]. A study of domestic buildings in UK show that savings from building envelope retrofits can be over estimated by 30 % when based on calculations only [5]. In case of old buildings, it was shown that the savings from retrofits were overestimated in 77 % of cases [5].

A better measure for building performance is to measure the building parameters, such as overall heat transfer coefficient, solar aperture and building time constants etc., also known as the intrinsic performance measurement [6]. The intrinsic performance measurements remain fairly stable with changing weather conditions, operation schedule etc.

The overall heat transfer coefficient H, the most popular parameter for building performance measurement [6,7], gives a measure of building heat loss $\dot{Q}$ due to temperature difference ΔT between the building and its environment:

$$H = \frac{\dot{Q}}{\Delta T} \quad (1)$$

This include losses via building surfaces and infiltration. A simple equation presenting the calculation of overall heat loss coefficient H from the stated building properties is [6,7]:

$$H = \sum_i U_i A_i + H_{TB} + \rho c_p \dot{V}_{inf}, \quad (2)$$

where:

$U_i A_i$ product of heat transfer coefficient of building elements (U_i) and its area (A_i);
H_{TB} thermal bridge heat loss coefficient;
$\rho c_p \dot{V}_{inf}$ infiltration losses.

Equation (2 is based on the thermal properties of the building that are used in design phase but that may change due to wear and tear, transfer of moisture through building envelope and missing insulation layers. The overall heat transfer coefficient is therefore determined using onsite test methods. The common onsite test methods discussed in literature are classified as [9]:

- long term or short term;
- intrusive or non-intrusive;
- controlled or non-controlled;
- measurement of individual building components such as walls, roofs etc. or of entire building.

Based on the available data and purpose of the identification, the methods can be either steady-state or dynamic.

Co-heating, calorific test method and flow meter test are long term, steady state test methods. The co-heating test method is the most common long term method; it is considered as a reference method used as a benchmark for the other methods. The co-heating test method involves heating the building at a constant temperature and measuring the required power input, the solar radiations and outdoor temperature during the test [10]. The overall heat loss coefficient is estimated using:

$$\dot{Q}_{heating} + gA_s = H(T_i - T_e) \quad (3)$$

where

$\dot{Q}_{heating}$ heating power supplied to keep the temperature constant;
gA_s solar power received by the building;
H overall heat transfer coefficient;
T_i indoor temperature of the building;
T_e ambient temperature of the external environment.

The required time duration for co-heating is at least two weeks but can increase up to a month. Since the method is performed in empty buildings and the duration is long, it is difficult to employ it as part of regular energy audits. Short term test methods can be used to circumvent the problem of long duration [11]. ISABELE, PSTAR and QUB are some of the short term, dynamic test methods.

QUB method is the shortest method among the thermal performance test methods. It involves the application of power as a step input. The method commences after the sunset and involves a heating phase followed by a cooling phase. The method can be performed in a single to two nights [11].

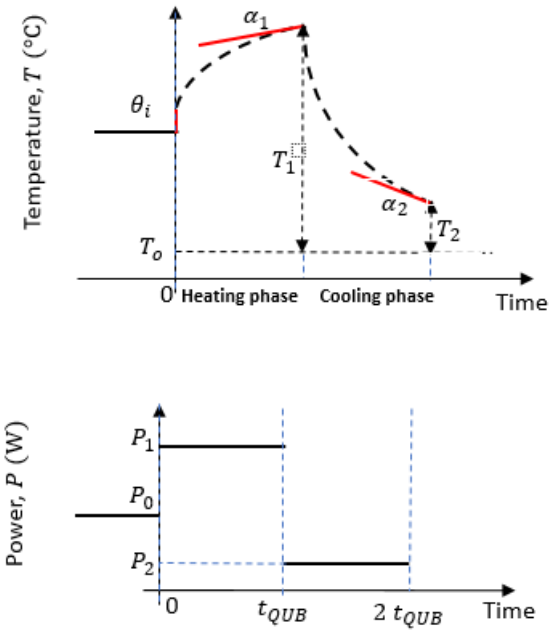


Figure 1: QUB test method and steps

In QUB test method, the overall heat loss coefficient is estimated as:

$$H_{QUB} = \frac{\alpha_1 P_2 - \alpha_2 P_1}{\alpha_1 T_2 - \alpha_2 T_1} \tag{4}$$

where:

- α_1 slope of the measured indoor temperature at the end of heating phase;
- α_2 slope of measured indoor temperature at the end of cooling phase;
- P_1 input power during heating phase;
- P_2 input power during cooling phase;
- T_1 temperature difference between indoor and outdoor temperature at the end of heating phase.
- T_2 temperature difference between indoor and outdoor temperature at the end of cooling phase.

The outdoor temperature is estimated by taking the mean temperature during night.

3.1. Influence of outdoor temperature variation during QUB experiment

QUB method is based on the evolution of indoor temperature derived from the differential equation:

$$C\frac{dT_i}{dt} = P - H(T_i - T_o) \tag{5}$$

where:

- α_1 slope of the measured indoor temperature at the end of heating phase;
- C apparent heat capacity or thermal mass of the building;
- T_i indoor air temperature;
- P power input during heating phase;
- T_o ambient/outdoor temperature.

The conditions for the derivation of QUB equation (4) from equation (5) are that the outdoor temperature should remain constant during heating and cooling phases [13]. A constant value of power is maintained before the experiment [14]. The power dissipated during the cooling phase

should be zero i.e. $P_2 = 0$. The method assumes that homogeneous internal temperature is maintained inside the building; in case of a house with many rooms, the temperature during heating and cooling phases inside each room should be ideally the same, a condition that is difficult to achieve in real experiments. There should be no air stratification (temperature difference along the height of the room) inside individual zones. The test should be carried without any occupants inside [8].

Ideally, QUB experiment should start from the steady state conditions. The literature however does not mention how long before the QUB test an initial steady state should be maintained [13].

The temperature evolution during the QUB experiment depends on the initial internal air temperature as well as the distribution of different temperatures inside the building envelope. Before the start of QUB experiment, the building should be in steady state [14]. The power input is from an electric heater as the heating from gas or boiler requires conversion efficiencies for power calculation that can increase the errors.

To reduce the variance of QUB results, a dimensionless quantity α, is introduced:

$$\alpha = 1 - P_o/P_1 \tag{6}$$

where P_o is given as [15]:

$$P_o = HLC_{ref}\, \Delta T_o \tag{7}$$

where $\Delta T_o = T_{io} - T_{eh}$ is the temperature difference between initial indoor temperature and the average outdoor temperature during QUB night. Ideally, this difference should be larger than 10 K. Since HLC_{ref} in equation (7) is not known in advance of the QUB experiment, it can be determined from either the design value or from calculations using envelope surface properties [14]. The power should be optimized based on the value of α [14]. The heating and cooling phases should be of equal durations. The theoretical model shows a strong dependence on α value. For experiments, it is recommended that α should be between 0.4 and 0.7 [14].

The robustness of the method was tested by numerical and physical experiments. The method was tested on a detached house, apartment building in controlled and real environments [9, 12, 14, 16]. The results of the experiments show that QUB method can generate results within $\pm$ 16 % of the reference overall heat loss coefficient (HLC_{ref}) (obtained via co-heating experiment). The simulation of QUB experiments for non-ideal weather conditions and a well insulated house (large temperature variation during the experiment night) show that results within $\pm 20\%$ of the reference H [12].

A method for the design of experiment by simulation was developed in which the error can be predicted for any power and time duration [17]. It was shown that the QUB experiment can be performed with duration of time shorter than the second largest time constant of the building and that QUB method is robust the variation of optimum power during the heating phase [12]. The method shows also robustness with variation in the insulation level of the building for which the experiment was originally designed such that even with 50% error in overall heat loss coefficient, the QUB errors lies within $\pm$ 15 % of the reference value [12].

The robustness of QUB experiment was tested on a real house [8]. The indoor temperature was maintained at steady state value using thermostatically controlled heaters. The house was tested between the end of September and the end of April. The experimental reported errors for QUB test were within $\pm$ 10 % of the steady state value of the overall heat transfer coefficient. There was no influence of α criteria on the results, provided that the α-value was maintained in the range of $0.4 < \alpha < 0.6$ [8,21]. When $\alpha > 0.7$, the results were consistently within $+$ 10 % region. The results of the experiments performed on real house showed that there is no correlation between the wind speed and H-value of the QUB method, although it was argued that the house was sheltered from three sides and only the West side of the house was exposed [8]. The QUB experiments for an apartment building showed that results were in good agreement with steady state test method [18] . Some of the variance (with a determination coefficient of 0.21 to 0.16) in QUB results can be attributed to external temperature, where an increased external temperature can increase the H-value measured with QUB method [8].

The variation in results with change in test conditions and wall configuration should be established. The performance of the method when ideal conditions are not respected during the

experiment should be analysed further [14]. This work aims to simulate the QUB experiments under non-ideal conditions during the experiment. The QUB experiments are also simulated for winter and summer seasons to analyse the suitability of particular season for QUB experiments.

2. Model description and validation

In order to simulate the QUB experiments under non-ideal conditions, a state space model is used. The model is generated in the steps: description of building components, generation of thermal circuits, assembling of thermal circuits, conversion of assembled circuits to state space model, and numerical simulation of the model with weather and indoor power data [18]. The method has the advantage of obtaining the model of the building as a single matrix. This allows us to obtain the eigen values and time constants of the building that can be used to analyse QUB method. The state-space modelling method also offers a transparent way of running the simulations, controlling the time step for simulation, changing the geometry of buildings, changing layers and components of the envelope. The weather data can be manipulated conveniently to determine the influence of boundary conditions, such as solar radiations, outdoor temperature etc. [12].

A model calibrated on a real house is used to simulate the QUB experiments. The house consists of attic, ground floor and basement [19]. The ground floor of the house is used to simulate QUB experiments, while the ground floor and the basement are maintained at constant temperature of 20 ℃. The ground floor consists of seven zones: kitchen, doorway, two bedrooms, bathroom, corridor, and living room. The blinds on Southern face are kept closed to reduce the influence of the solar radiation. The outdoor ventilation system in the house is closed during the experiments.

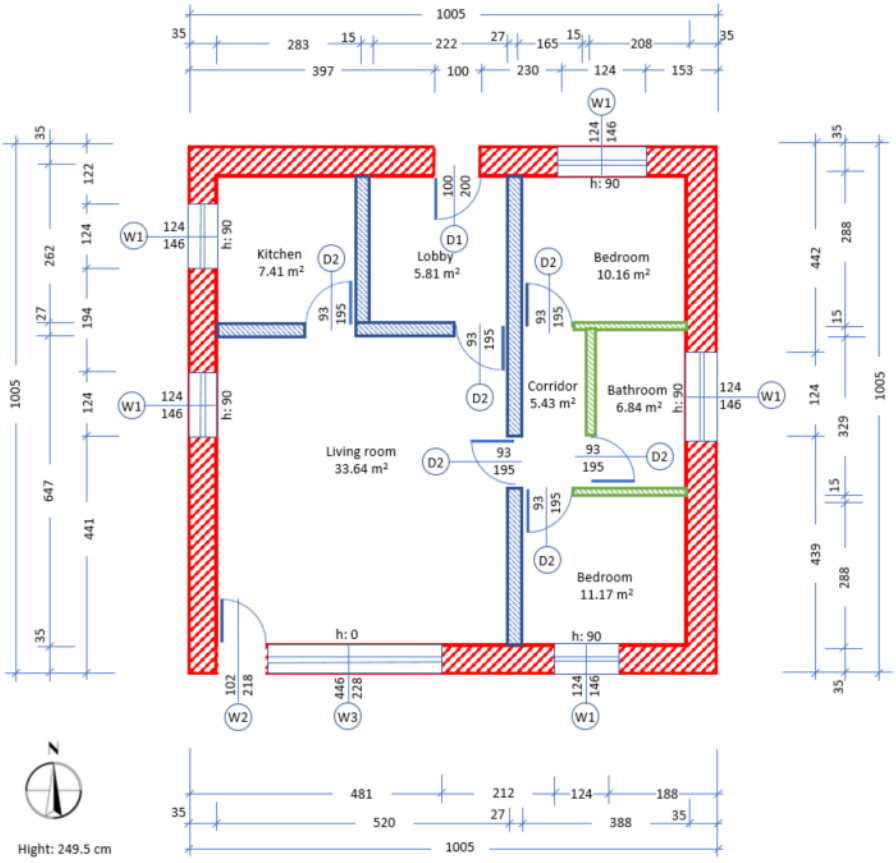


Figure 2: The twin house layout and dimensions (centimetres)

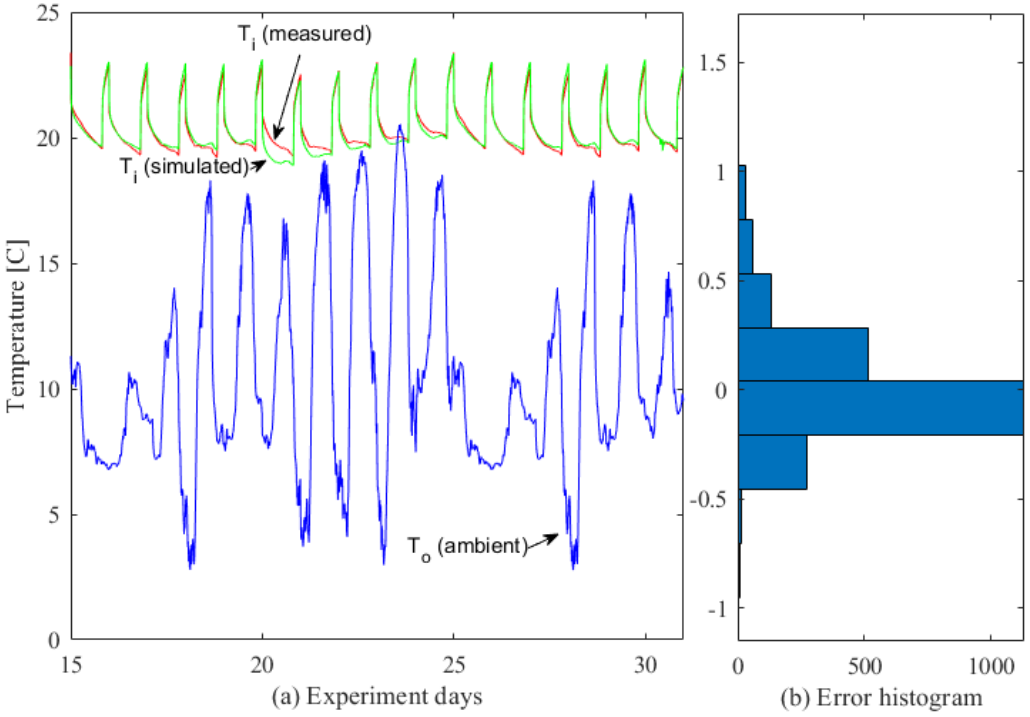


Figure 3: QUB experiments (a) simulated temperature (red line) comparison with measured temperature (green line) and outdoor temperature (blue line) (b) Simulation error histogram

In addition to the experiments conducted in IEA Annex 58 [19], QUB experiments were performed in this house for 15 days during the spring of 2014 [14]. The cellar was kept at constant temperature of 20 ℃ to reduce the heat flow. The QUB experiment was performed fifteen minutes after the sunset every day. Heating was done with floor mats of 115 W in vertical position to avoid air stratification; the ventilation system was turned on to further improve the temperature homogeneity of the air in the rooms [14].

The experimental data from the QUB experiments was used to validate the simulation model used for numerical QUB experiments (Figure 3). The cellar and the attic zones were considered as boundary conditions. It can be observed that the simulation model (kitchen zone) follows the measured temperature within ±0.5 ℃ (Figure 3). The increased errors on day 5 and 6 are due to the missing temperature data.

The purpose of this work is to analyze the accuracy of QUB method with changing indoor and outdoor conditions. The analysis are performed by simulating QUB experiments using the construction data of the twin house (Figure 2) and recorded weather data [20]. The experiments are performed by simulating the evolution of indoor temperature during the heating and cooling phases of QUB experiment with the weather conditions of the outdoor environment. An overall heat transfer coefficient obtained using steady state method is used as benchmark for comparison with QUB experiments. Assuming that the height of each zone is the same, the steady state overall heat transfer coefficient is:

$$H_{ref} = \frac{\sum_i P_i}{\frac{\sum_i A_i \theta_i}{\sum_i A_i} - T_o} \tag{8}$$

where:

P_i ipower supplied to each zone/room of the twin house, W;
A_i surface area of each room, m^2;
θ_i temperature of each room, °C;
T_o uutdoor temperature, °C.

To the estimate the steady state overall heat transfer coefficient, an experiment is designed where a constant power is supplied to each room at a given outdoor temperature and the indoor temperature of each zone is measured. The overall heat transfer is then estimated using equation (8). The overall heat transfer coefficient estimated in this case was 90 W/K.

3. Empirical analysis of the influence of non-ideal conditions

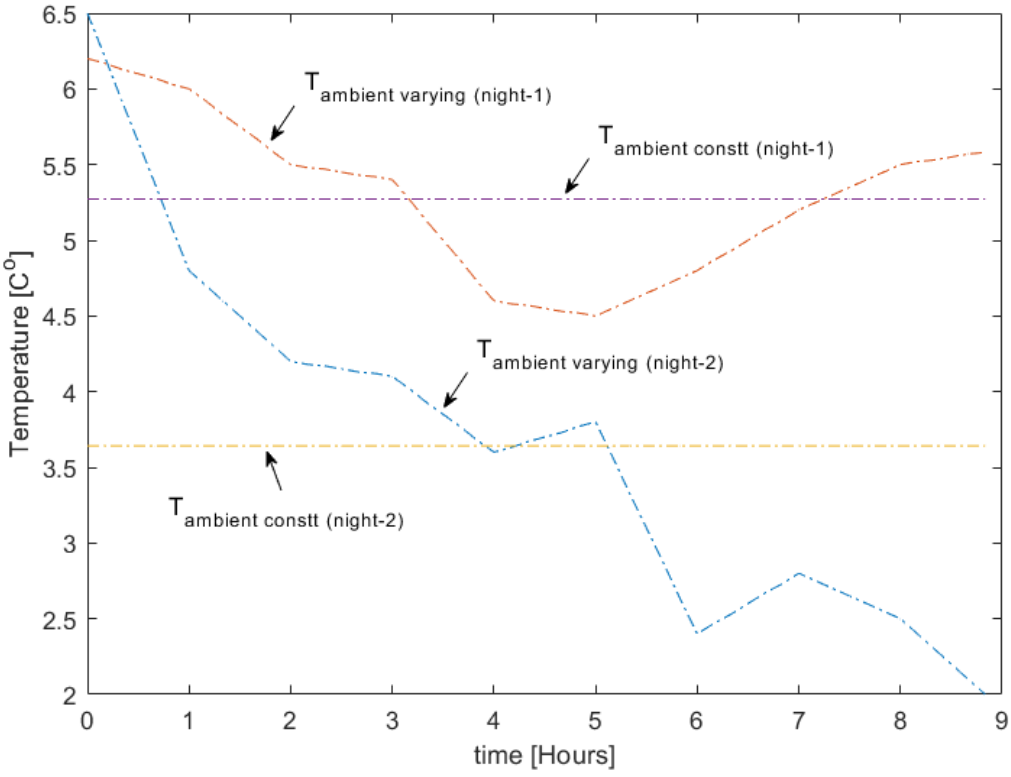
3.1. Influence of change in building envelope state/temperature

The derivation of the QUB experiments assume that the external temperature is constant during heating and cooling phases [13]. This condition may not be respected in real experiments where the temperature can vary during both phases. The outdoor temperature variation and the assumed constant outdoor during a typical QUB night are shown in Figure 4.

It is interesting to find the impact of variation in outdoor temperature on the QUB results when the perfect conditions of constant outdoor temperature are not respected during the test. Two sets of QUB experiments are performed for winter months starting from November to end of March (150 days) for the weather data of Munich, Germany. One set of experiments is performed with constant outdoor temperature and the other set is performed with varying outdoor temperature during the QUB experiments.

Figure 5 shows the results when the QUB experiments are performed:

- at the real outdoor temperature with normal variation during the QUB night;
- at the assumed constant outdoor temperature by taking the average outdoor temperature during the experiment night.



- Figure 4: Temperature variation during a typical night for QUB experiment; horizontal dashed line shows the assumed constant temperature during the QUB night

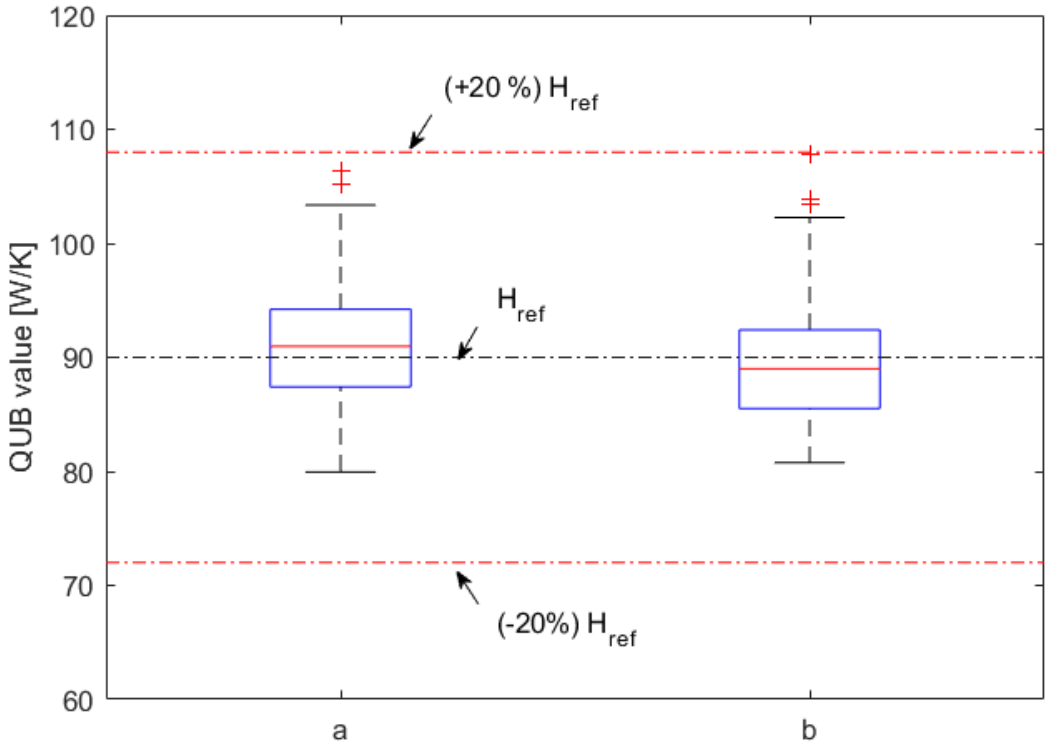


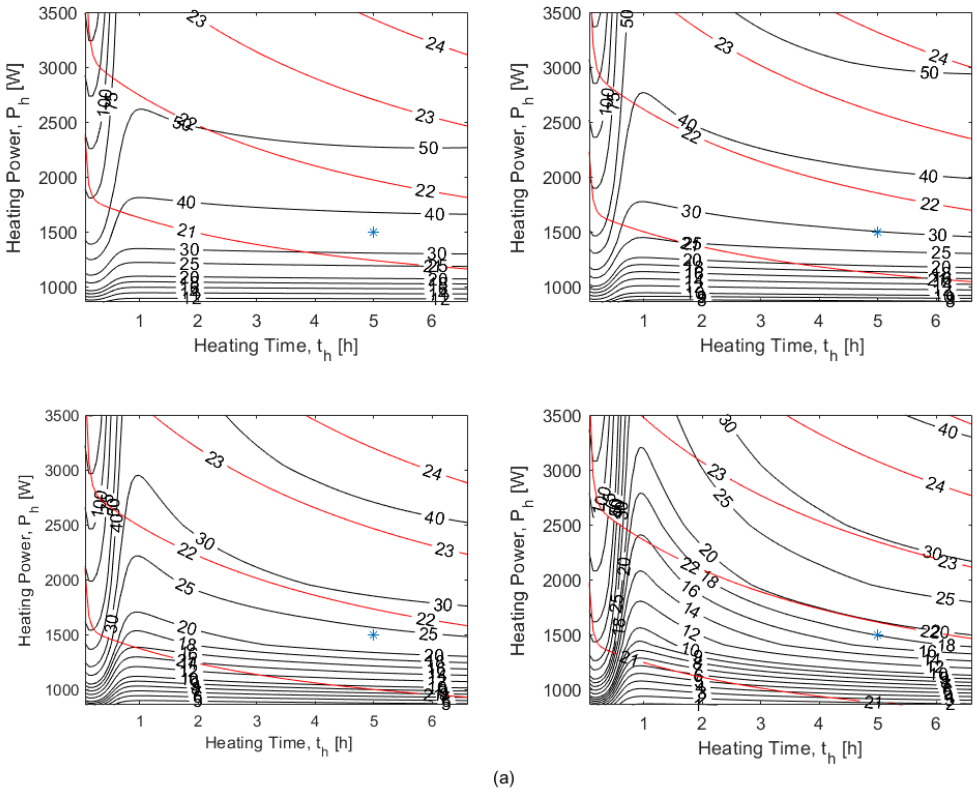
Figure 5: Comparison between QUB results at (a) varying outdoor temperature and (b) constant outdoor temperature. The black dashed line shows the steady state overall heat transfer coefficient and the two red dashed lines show $\pm 20\,\%$ of the steady state overall heat transfer coefficient.

The results of QUB experiments for both conditions (a) and (b) lie within $\pm\,20\,\%$ of the steady state overall heat transfer coefficient. Figure 5 shows that, with both constant and variable outdoor temperature, QUB results are relatively similar.

3.2. Influence of change in building envelope state/temperature

QUB experiment can be designed if a simulation model is available [17]. For any simulation model to accurately predict the error in QUB experiment, the initial conditions (i.e. the values of the temperature in the walls of the building) need to be correctly defined. The inability to realize the true states of the building envelope can lead to erroneous predictions. The error curves in Figure 6 are generated for the same house at the same outdoor temperature and power levels during QUB experiment. However, the initial states i.e. the initial temperature of the surfaces and layers of building were different during each simulation. The different initial states are generated by changing the temperature of the building surface layers before the start of the simulation of QUB experiment.

The results of simulation show that, with the changed states, QUB error also changes Figure 6(a). The error curves in Figure 6(b) are generated for the same building but with different temperature/states of building envelope; the red dashed line shows that an experiment at the same power, outdoor temperature and time passing will result is different errors. A design of experiment therefore may not be relied upon if the real states of the building are not taken into account during QUB experiment. This also helps us understand that with the changed states, every time a QUB experiment is repeated, the results will be changed.



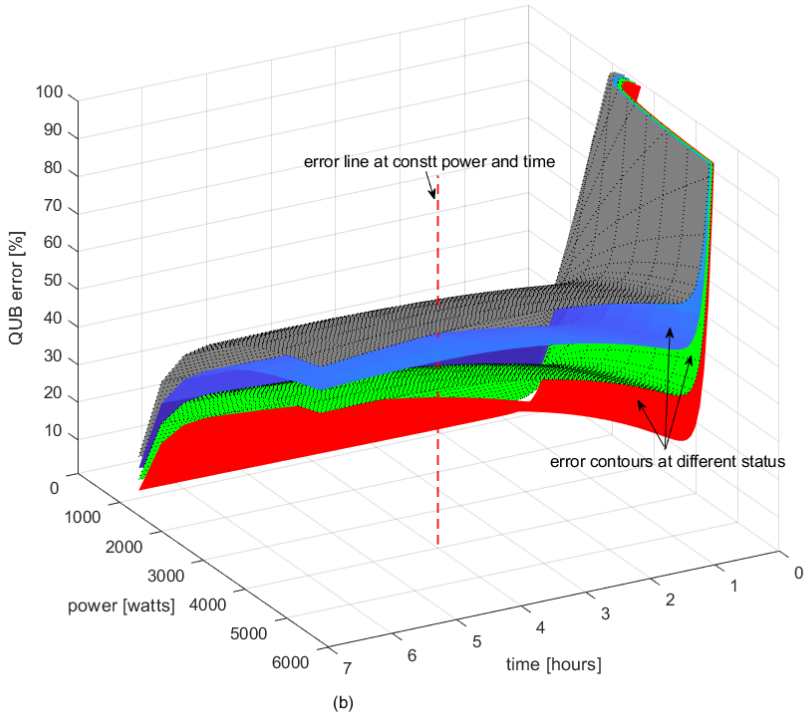


Figure 6: QUB error when the initial states in simulation are different but the outdoor temperature and power are the same during QUB experiment. (i) top left 35 %, (ii) top right 30 %, (iii) bottom left 24 % and (iv) error is 12 %. (b) The same experiments as in (a) but with error curves shown in 3D (errors shown by the red vertical line)

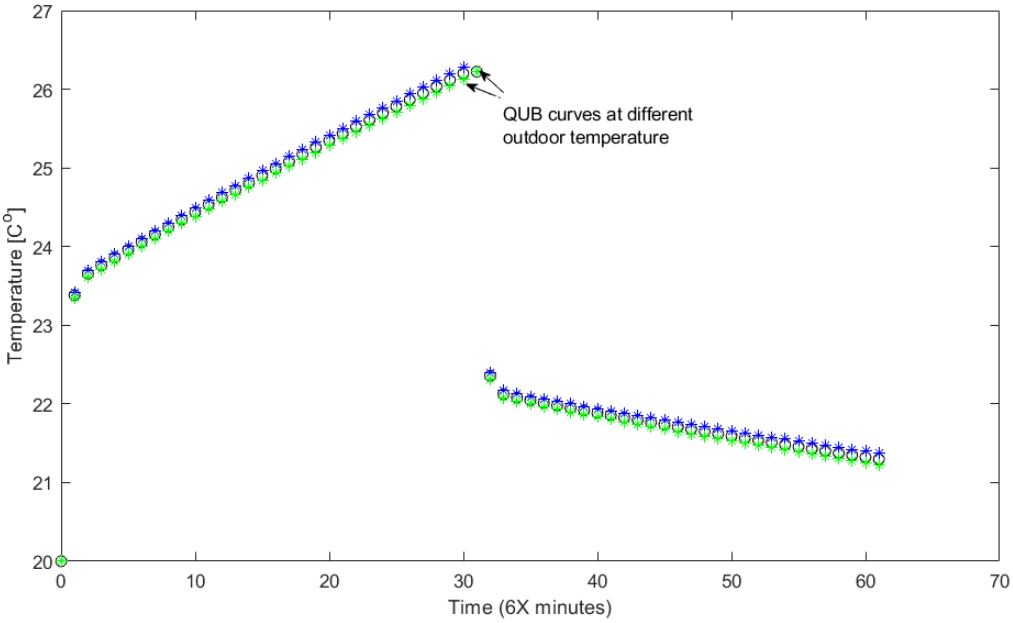


Figure 7: The indoor air temperature response when temperature during QUB experiment at different outdoor temperatures i.e. at predicted temperature (black circles), at -20% of the predicted temperature (green asterisks) and at $+20\%$ of the predicted temperature (blue asterisks)

3.3. Influence of meteorological conditions

The change in meteorological conditions during QUB experiment can change the results. The design of QUB experiment depends on the predicted temperature during the experiment. It is expected that outdoor conditions can deviate from the predicted weather conditions. The effects of meteorological uncertainties can be reduced by performing QUB experiment at higher level of power [22]. To analyze the effect of metrological uncertainty, a QUB experiment was simulated at power level of 5000 W during the heating phase. The experiment was simulated at the predicted outdoor temperature and then repeated at the ± 20 % of the predicted temperature (Figure 7). It can be observed that the responses at different outdoor temperatures are only slightly different (Figure 7). QUB results with variation of outdoor temperature are in a range of error less than 5 %.

3.4. Influence of seasons (winter and summer)

Since the results of QUB experiment depend on outdoor conditions, QUB experiments were simulated during summer and winter seasons. Hourly weather data for the city of Munich [20] was used to simulate the QUB experiment on a house specified in IEA, EBC Annex-58 [19]. The data was interpolated to generate data at sample time of 10 minutes. The applied power was optimized using $\alpha = 0.5$ (see eq. (9)) with no power during the cooling phase. Figure 8 shows the results for November to March and for June to August. The heating and cooling phase has a length of 4.5 hours. The results of the experiment show that in winter season (November to March) QUB experiments have less error and variation. The majority of the results are within $\pm\, 20$ % of the reference overall heat coefficient (Figure 8 box plot on left).

For the summer season (June, July, August), the QUB experiments show large variation. The majority of QUB experiments show an under estimation (Figure 8 box plot on right). The set temperature before the start of QUB experiments was maintained at 20 ℃ during these experiments. It may be mentioned that the majority of the in-situ overall heat transfer coefficient testing methods are recommended for seasons where a minimum temperature difference of 10 K can be maintained between indoor and outdoor temperature, a condition that is difficult to achieve during summer time [3].

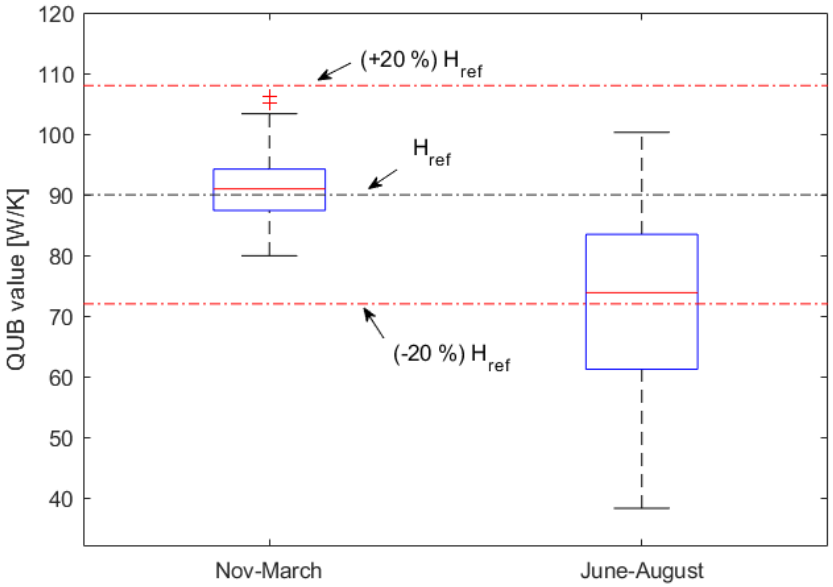


Figure 8: Errors of QUB experiments performed during three seasons: winter and summers. The black dashed dotted line shows the steady state overall heat transfer coefficient and the two red dashed dotted lines show $\pm$ 20 % of the steady state overall heat transfer coefficient.

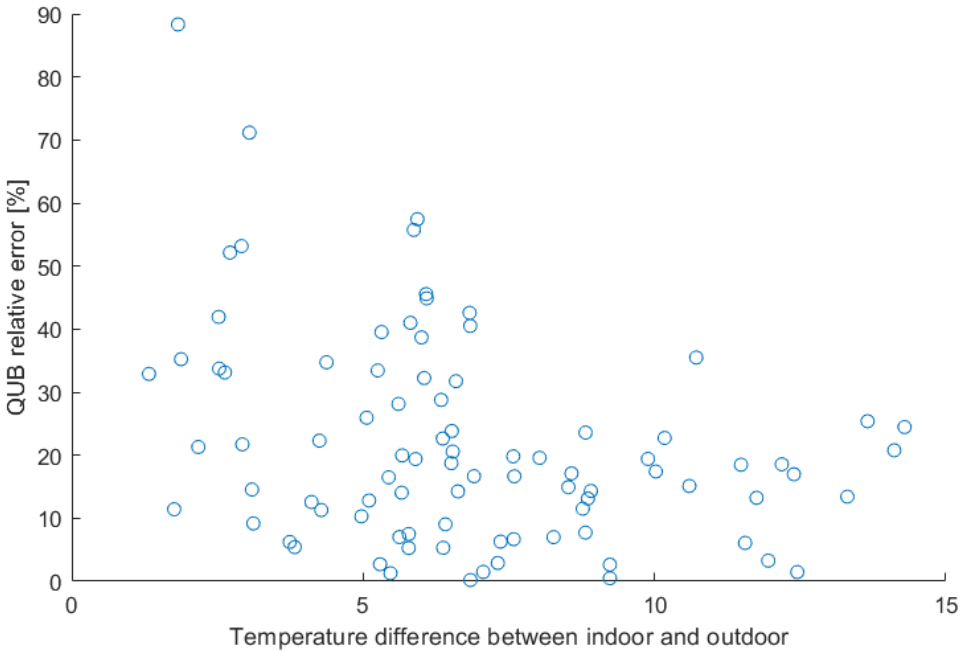


Figure 9: QUB error as a function of difference between outdoor and indoor temperature before the start of experiment

The under estimated QUB results during the summer season coincide with high outdoor temperatures during QUB experiments, i.e. a low temperature difference between indoor and outdoor temperature before the start of QUB experiment.

Figure 9 shows the temperature difference at the time of the beginning of QUB experiments during summer months and QUB error. It is evident that the small temperature difference between

outdoor and indoor temperature results in larger errors. It can be seen that with the temperature difference above 10 K, the error remains within ± 20 %.

It can be concluded that winter is a better season for QUB experiment. In summer, the variation and error in QUB experiment is relatively large due to small temperature difference between indoor and outdoor temperatures.

The large errors during summer can be understood with respect to the optimum power during the heating phase of a QUB experiment, that can be given by the α-criterion [15]:

$$\alpha = 1 - P_o/P_1 \tag{9}$$

where P_o is computed as $HLC_{ref}\Delta T_o$. An acceptable range for α should be between 0.5 to 0.7 [15]. The heating power P_1 therefore can be given as:

$$P_1 = n\, HLC_{ref}(T_{indoot} - T_{outdoor}) \tag{10}$$

where n should be between 2 to 4 for α to be between 0.5 to 0.7. During summer, the temperature difference between indoor (set at 20 °C) and outdoor is small. During summer days, with the temperature difference smaller than 10K, experiments with $\alpha = 0.5$ i.e. $n = 2$ in equation (10) results in a small power during heating phase, producing an under estimation of overall heat transfer coefficient as shown in Figure 8 (box plot for summers).

In order to increase the temperature difference in summer, QUB experiments were repeated with a higher set point temperature of 25 °C before the start of the experiment. The experiments show that, at high indoor set temperature, the results of QUB experiment improve (Figure 10). The majority of QUB results are within ± 20 % of the steady state overall heat transfer coefficient with few outliers. The results are further improved by increasing the power ratio ($\alpha = 0.7, n = 3$). An increase in power ratio α above 0.7 results in over estimation of QUB results.

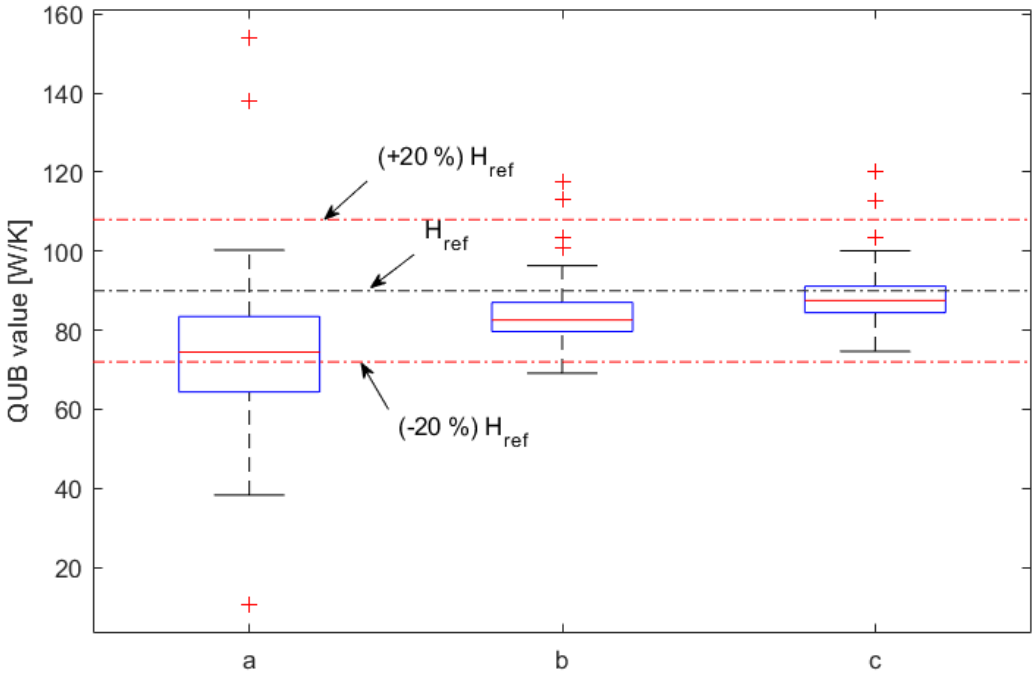


Figure 10: QUB experiments when simulated at (a) 20C set point temperature and alpha = 0.5 (n=2), (b) 25C set point temperature and alpha = 0.5 (n=2) (c) 25C set point temperature and alpha = 0.67 (n=3)

3.5. *Optimum power for winter*

To determine the optimum power for winter, a number of experiments were performed from November to March at different levels of heating power with n ranging from 2 to 6. The results can be viewed in Table 1. It can be observed that with n between 2 and 3, QUB results are closer to the steady state overall heat transfer coefficient. It must be mentioned that the value of n is valid for a temperature difference that is above 10 K. The extreme outdoor conditions, such as an extremely cold outdoor temperature, can lead to a high power, even with n lower than 2.

Table 1: QUB experiment during winter months at different levels of power

n	2	3	4	5	6
QUB overall heat transfer coefficient [W/K]	91	95	99	103	107
Standard deviation	8	7.6	7.3	7.07	6.8
Steady state overall heat transfer coefficient			90		

3.6. QUB experiments for buildings with lower overall heat transfer coefficient

QUB experiments presented above were simulated for a house that has relatively high level of insulation with an overall heat transfer coefficient value of 90 W/K. In order to determine the behavior of QUB method for buildings with low level of insulation, QUB experiments were simulated for the same house but with the overall heat transfer coefficient of 134 W/K and of 179 W/K. Experiments were simulated for one year. It can be inferred from results shown in Table 2 that, with the reduced insulation, the median error for the QUB experiments is reduced.

Table 2: QUB experiments at different insulation level of building

$\mathbf{H_{ref}}$ **(steady state)**	**90**	**134**	**179**
Median H_{QUB} [W/K]	84	128	172
Median error (%)	8	6	5

4. Conclusions

This work discusses the ideal conditions for QUB test and then simulates QUB experiments for a real house in non-ideal weather conditions. The model used to simulate QUB experiments is validated using IAE, Annex 58 data set along with real QUB experiments conducted in the same house. Weather data for Munich is used to simulate QUB experiments for the ground floor of house. The results of simulation experiments can be concluded as follows.

The QUB experiments were simulated with variable and constant outdoor temperature during the night. Majority of the errors for variable and constant outdoor temperature (during QUB experiment) lie within $\pm 20\,\%$. The variation of QUB results for variable and constant outdoor temperature were relatively similar.

The simulation results of QUB experiment can vary with the initial conditions of the building envelope. The reason QUB experiments show variations when repeated is that between two experiments the states/temperature of the building envelope cannot remain the same.

The meteorological conditions for which QUB experiment is designed may vary, i.e. the outdoor temperature can increase or decrease during QUB night. A $\pm 20\,\%$ variation in outdoor temperature change QUB results within $\pm 5\ \%$.

A comparison of QUB experiments for summer and winter show that the cold season can be considered more suitable for QUB experiments. Experiments conducted for the month of November,

December, January, February and March show that the majority of the errors lie within ± 15 % with few outliers around ± 20 %.

QUB experiments for summer months (June, July and August) show large variation (errors). However, it is possible to predict the experiment outcome by observing the difference between indoor temperature and outdoor temperature during QUB experiment. The experiments give large errors when the temperature difference between the initial indoor and outdoor temperature is smaller than 10 K. With set point of $20℃$ the difference between indoor and outdoor temperature for few days remained smaller than 10 K. The experiments in such conditions generated large errors. The results during summer days were improved by using a high set point temperature (25 ℃), such that majority of the errors remained within ± 20 ℃ of the steady state overall heat transfer coefficient. The summer results can be further improved by using a high power ratio, i.e. $\alpha = 0.7$.

QUB experiments for winter show results close to steady state overall heat transfer coefficient when α-value (ratio of power during heating and cooling phase) is between 0.5 to 0.7.

The performance of QUB method show that method can respond well for buildings with reduced insulation.

Author contributions: conceptualization, C.G.; data curation, M.Q.; formal analysis, C.G.; investigation, N.A.; methodology, N.A. and C.G.; project administration, C.G.; software, N.A.; supervision, C.G.; validation, M.Q.; writing–original draft, N.A.; writing–review & editing, C.G. and M.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partly funded by Campus France and Higher Education Commission (HEC), Pakistan (80 %), through a doctoral scholarship awarded to Naveed Ahmad and partly (20%) by Saint Gobain, through a research contract.

Acknowledgments:. The description of the building and the experimental data were provided by Fraunhofer-Institut für Bauphysik IBP, Holzkirchen, 83626 Valley, Germany. The support of Paul Strachan from Energy Systems Research Unit, University of Strathclyde, Glasgow, G1 1XJ, UK, and Ingo Heusler and Matthias Kersken from Fraunhofer-Institut für Bauphysik IBP, Holzkirchen, 83626 Valley, Germany are highly appreciated. The continuous inputs and recommendations of Thimothee Thiery, Research Engineer at Saint Gobain, are highly appreciated.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. O. Lucon et al., "Buildings," in Climate Change: Climate Change Mitigation, Contribution of Working Group III to Fifth Assess. Report. Intergovernmental. Panel on Climate Change., vol. 33, pp. 1–66, 2014.
2. Energy Information Administration - EIA - Official Energy Statistics from the U.S. Government EIA - "International Energy Outlook 2019". Retrieved from official website of US Energy Information administration website: www.eia.gov/outlooks/ieo/pdf/ieo2019.pdf.
3. G. Bauwens and S. Roels, Co-heating test: A state-of-the-art, Energy and Buildings, vol. 82, pp. 163–172, 2014.
4. C. Demanuele, T. Tweddell, and M. Davies, Bridging the gap between predicted and actual energy performance in schools, World Energy Congress XI, Abu Dhabi, UAE, 23-25 September, 2010.
5. A. Rasooli, L. Itard, and C. I. Ferreira, A response factor-based method for the rapid in-situ determination of wall's thermal resistance in existing buildings, Energy and Buildings, vol. 119, pp. 51–61, 2016.
6. A. Brun, F. Alzetto, P. Boisson, and S. Thebault, Short methodologies for in-situ assessment of the intrisinc thermal performance of the building envelope, in Sustainable Places, 2014.
7. A. Janssens, Statistical Guidelines: Reliable building energy performance characterization based on full scale dynamic measurements in Buildings, Retrieved from the official website International Energy Agency website: https://www.buildup.eu/en/explore/links/iea-ebc-annex-58-0, 2014.
8. V. Sougkakis, J. Meulemans, F. Alzetto, C. Wood, and T. Cox, An assessment of the QUB method for predicting the whole building thermal performance under actual operating conditions, in International SEEDS Conference, 2017.
9. A. Foucquier, S. Robert, F. Suard, L. Stephan, A. Jay, and L. Stéphan, State of the art in building modelling and energy performances prediction: A review, Renewable and Sustainable Energy Reviews, vol. 23 pp. 272-288, 2013.

10. S. Stamp, H. Altamirano-Medina, R. Lowe, Assessing the Relationship between Measurement Length and Accuracy within Steady State Co-Heating Tests, Buildings, 7(4), 98, 2017.
11. N. Ahmad, C. Ghiaus, T. Thiery, Influence of Initial and Boundary Conditions on the Accuracy of the QUB Method to Determine the Overall Heat Loss Coefficient of a Building, Energies, vol. 13, no. 1, pp. 1–24, 2020.
12. G. Pandraud, G. Didier, and F. Alzetto, Experimental optimization of the QUB method, in IEA–EBC Annex 58, 6th Expert meeting, 2014.
13. A. Florent, G. Pandraud, and R. Fitton, QUB: a fast dynamic method for in-situ measurement of the whole building heat loss, Energy and Buildings, vol. 174, pp. 124–133, 2018.
14. J. Meulemans, F. Alzetto, D. Farmer, C. Gorse, "QUB/e: A novel transient experimental method for in situ measurements of the thermal performance of building fabrics, in International Sustainable Ecological Engineering Design for Society (SEEDS) Conference, September 2016.
15. F. Alzetto, D. Farmer, R. Fitton, T. Hughes, W. Swan, Comparison of whole house heat loss test methods under controlled conditions in six distinct retrofit scenarios, Energy and Buildings, vol. 168, pp. 35–41, Jun. 2018.
16. C. Ghiaus and F. Alzetto, Design of experiments for Quick U-building method for building energy performance measurement, Journal of Energy and Buildings Performance Simulation, DOI: 10.1080/19401493.2018.1561753.
17. J. Meulemans, An assessment of the QUB/e method for fast in situ measurements of the thermal performance of building fabrics in cold climates, in Cold Climate HVAC 2018 - The 9th International Cold Climate Conference, Lund University, Kiruna Sweeden, 2018.
18. C. Ghiaus, N. Ahmad, Thermal circuits assembling and state-space extraction for modelling heat transfer in buildings, Energy, vol. 195, p. 117019, Jan. 2020.
19. P. Strachan, I. Heusler, M. Kersken, M. J. Jiménez, Empirical Whole Model Validation Modelling Specification Validation of Building Energy Simulation Tools, 2016 Retrieveid from the official website International Energy Agency wbesite: https://www.buildup.eu/en/explore/links/iea-ebc-annex-58-0.
20. Weather Data | EnergyPlus. Available: https://energyplus.net/weather. [Accessed: 02-Apr-2020].
21. F. Alzetto, J. Meulemans, G. Pandraud, and D. Roux, A perturbation method to estimate building thermal performance, Comptes Rendus Chimese, vol. 21, pp. 938–942, 2018.
22. J. Meulemans, F. Alzetto, D. Farmer, and C. Gorse, QUB/e: A Novel Transient Experimental Method for in situ Measurements of the Thermal Performance of Building Fabrics, in Building Information Modelling, Building Performance, Design and Smart Construction, Cham: Springer International Publishing, 2017, pp. 115–127.