Statistical Analysis of the Factors influencing the In Situ U-Value of Walls

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ABSTRACT

Building thermal performance testing requires in situ measurement techniques that are well supported and validated by simulation with statistics to improve the accuracy of the results. Local on-site performance of building components is different from the theoretical one, influenced by factors affecting the building's thermal conditions. The current paper reviews the factors influencing the measured U-value results in the heat flux method based on quantitative findings of other studies through regression and correlation statistics. The findings regarding the current status of knowledge are limited to in situ methods without detailed insights of response time, sensitivity analysis, and thermal boundary conditions in the local context. Regression analysis between wall characteristics, time duration, temperature difference, and the measured U-value shows a very strong and statistically significant impact of these variables on the accuracy of the measured U-value of low transmittance walls. The R^2 value indicates that three variables can collectively explain 91% of the variance in the measured U-value. There is a linear correlation between the wall characteristics and the measured U-value and a non-linear correlation between the time duration, temperature difference, and the measured U-value. Future work will focus on developing a measurement framework that considers time-dependent variables, dynamic weather, and uncertainty with high accuracy for different boundary conditions.

Keywords-thermal measurement; in situ measurement; U-value; heat flux method; regression analysis

I. INTRODUCTION

"If you cannot measure it, you cannot improve it" Lord Kelvin's famous quote applies to building energy use [1]. In situ, testing and dynamic data analysis are prerequisites for quantifying the actual performance of buildings and verifying the mathematical equations that describe it. The dataset obtained through in situ testing will also help validate the building simulation results. In situ testing is more complex in solution than in practice, and questions are raised regarding its accuracy and reliability. A high-quality method is required, starting with the test environment, sensors' quality and calibration, correct experimental setup, and data analysis. Thermal transmittance value (U-value) measurement and accuracy are crucial for the evaluation of the energy performance. Very few empirical studies have been conducted to identify the factors that influence the accuracy of numerical data. Management of zero-energy buildings requires monitoring techniques that include the thermal performance of the building. Despite some real-time investigations, the data collection concerning the most influential parameters (U values, time duration requirements, and temperature differences) still needs to be answered. If taken care of, data utilization for determining the most significant parameters will provide almost accurate real-time U-values. About 91% of the variance in the measured U-value can be attributed to temperature difference, time duration, and wall characteristics. Near-zero buildings will require a higher temperature difference of $11°C<\Delta T<15°C$ with measurements in the transient state and a short time duration of 24 to 72 hr. A double wall with a low U-value and a low-temperature difference of <11°C demands a minimum time duration of 96–168 hr to reach the convergence value. This study will contribute to the field of performance testing and will widen the scope of taking up real-time building measurements.

Several green building rating systems, including GRIHA and LEED, do not ensure great performance [2] and satisfactory indoor air quality [3]. A significant gap was observed between the predicted and the actual performance of non-residential and residential buildings [4]. This performance gap persists in India [5]. No standardized protocol has gained international importance in assessing buildings in the use category. About 40% to 45% of the total heat load is due to the materials used and the design of the envelope, which is again governed by the U-value [6]. U-value also regulates the energy consumption and thermal comfort inside the building. The conductive heat flow was reduced due to the evaporation process with natural stones as a building material, which increased the thermal comfort inside with a reduction in energy consumption [7]. Natural convection heat transfer rates increase in an open enclosure with an air cavity with an aspect ratio of 2 [8].

II. BACKGROUND

Gaps have been found regarding real-time empirical studies required for experimentation, specifically in low and medium thermal transmittance values. Several studies have been conducted to compare in situ and theoretical measurement values, e.g. U-value measurements and calculations of the ceramic wall carried out in [9] utilizing the heat flux method (the most used method) showed 8.1% and 18.9% variations with different inside and outside temperatures. Measured and theoretical U-values for precast concrete construction demonstrated a variation ranging from 4% to 75% in [10]. The error percentage between measured and theoretical U-values ranged between 17% and 153% for complex wall compositions [11].

A. Heat Flux Method: A Static Procedure

This method has a worldwide application based on heat-flux sensors [12]. Data on heat flux and air temperature are the two fundamental requirements of this method. A long measurement time will converge to the value of the thermal resistance. This value is based on data measurements of the surface temperature and average heat fluxes. Two thermocouples were installed on each side and the outside wall. Also, a heat flux meter was installed. The heat flux sensors were selected based on the following:

- Expected ranges of heat flux and temperature.
- Mode of heat conduction, convection, and radiation transfer (specific boundary conditions).
- Special requirements of the environment (chemical and mechanical, as these conditions have adverse effects on sensors).
- Measurement of an output signal voltage.

B. Instrument Location

The installation of the heat flow sensor should be 1.5 m above the floor [13]. The location should be far from the cold bridges [14], and the sensor should be 1.3m from the radiators or fan coil units. To avoid convective effects, sensors that measure the internal and external air temperatures were placed 30 cm to 40 cm away from the vertical wall surface [15]. No air gaps should exist between the sensor and the surface, as they act like insulators. When the sensor remains fixed and is not in a moving condition during the experiment, the cables should not be forced to cause stresses and strain relief of the cable should be provided by a cable tie mount.

C. Transient Analysis – Excitation Pulse Method

The theory of response factors was adopted in [16], and became a principle for this method. This theory has been widely applied in building simulation software for the heat transfer modeling process. Excitation (cooling/heating) is applied on only one side of the wall to change the surface's temperature and heat flux response is measured and converted into wall response factors on both sides. The response factors were calculated from the thermal and physical properties of the wall. In this method, the internal surface temperature of the wall can be controlled by linear heating or cooling, which generates a triangular profile of the surface temperature. The heat fluxes on both sides of the wall were measured, and the response factor was calculated from a mathematical equation.

A radiative heater for heating and a convection fan for cooling were used for excitation. A box protects the exterior surface and the sensors and a data logger records the data [16]. Generally, to determine the maximum surface temperature, a duration of 15 min and a temperature range of 70 °C to 90 °C were found appropriate [17].

III. METHODOLOGY

The standard four-stage identification, screening, eligibility, and inclusion process was considered for review. Extensive literature research was conducted involving Scopus (2013-2023) and Google Scholar databases using the keywords "accuracy, in-situ, measurements, U value." Systematically conducted searches were performed by writing the keywords utilizing the Boolean operator "AND." Analysis of the search results revealed 74 documents from various disciplines. The initial screening after reading the abstracts led to 36 documents, and after the final screening of the complete text, only 14 papers were included. Only six studies were entailed in the review after examining the required factors and quantitative data. Very little work has been done regarding quantitative real-time assessment and the determination of the impact of time duration, temperature difference, and wall characteristics on the accuracy of the U-value.

TABLE I. QUANTITATIVE DATA TAKEN FROM THELITERATURE

Reference	Publication year
[18]	2017
[19]	2020
[20]	2018
[21]	2018
[22]	2018
[23]	2017
[24]	2019
[25]	2018
[26]	2016

A. Data for the Statistical Technique

Data were collected from the studies mentioned above with theoretical U-values of 0.27, 0.36, and 0.52 W/m^2K, and wall characteristics of (i) double-skin facade with internal insulation but no air cavities (thickness 0.33 m), (ii) four-layer wall panel incorporating a galvanized steel structure (thickness 0.30 m), (iii) double-skin facade with a non-ventilated air cavity and internal insulation, finished with continuous covering (thickness 0.34 m), time duration of 24, 48, 72, 96, 120, 144, and 168 hr and temperature differences of $\Delta T < 11$ °C, 11 °C $< \Delta T <$ 15 °C, and $\Delta T >$ 15 °C.

Pearson correlation was performed to determine if there was a correlation between the measured and the theoretical U-values. A high positive correlation result was found between the measured and the theoretical U-value with $r(33) = 0.95$, $p \leq 0.001$.

Multiple linear regression analysis was performed to examine the influence of the variables (temperature difference, time duration, wall characteristics) on the measured U value of low transmittance walls. It was hypothesized that they would positively predict the accurate results of measured U value. The regression model revealed (Table II) that the variables temperature difference explained 92.66% of the variance.

B. Linear Regression Assumptions

1) Quantile- Quantile (Q-Q) Plot

The model did not demonstrate any multicollinearity, which is problematic if tolerance < 0.10 or VIF > 10.

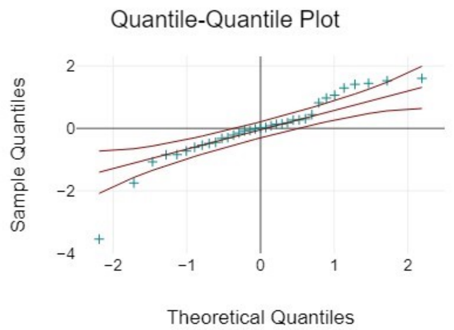

Fig. 1. Q-Q plot showing a normal distribution.

2) Multicollinearity

TABLE II. INDEPENDENT VARIABLE MODEL FOR TOLERANCE AND VIF

Model	Tolerance	VIF
Temperature difference 11 °C < ΔT < 15 °C	0.42	2.4
Temperature difference ΔT > 15 °C	0.63	1.6
Time duration (hr)	1	1
Wall characteristics: The panel consisted of a four-layer wall incorporating a galvanized steel structure with a total thickness of 0.30 m.	0.42	2.4
Wall characteristics: Double-skin facade with a non-ventilated air cavity and internal insulation, finished with continuous covering, with a total thickness of 0.34 m.	0.31	3.2

3) Heteroskedasticity

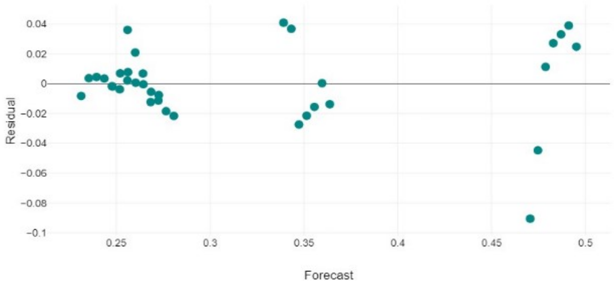

Fig. 2. Plot showing the assumption of heteroskedasticity.

The variance in the residuals was constant over the predicted values. The data did not show heteroscedasticity.

IV. RESULTS AND DISCUSSION

A. Model Summary

The model summary can be observed in Table III.

TABLE III. MODEL SUMMARY OF REGRESSION ANALYSIS.

R	R^2	Adjusted R^2	Standard error of the estimate
0.96	0.93	0.91	0.03

TABLE IV. ANOVA RESULTS

Model	df	F	p
Regression	5	73.18	<.001

Analysis of variance (ANOVA) was used to test whether this value significantly differed from zero (Table IV). It was found that the effect significantly varied from zero, with $F=73.18$, $p \leq 0.001$, $R^2 = 0.93$. The R-value (multiple correlation coefficient) showcases a strong correlation between the independent and the dependent variables. The greater the correlation, the better the regression model is. The coefficient of determination R^2 indicates that 93% of the variance of the dependent variable (measured U-value) can be explained by the three independent variables (temperature difference, wall characteristics, and time duration). The results denote that the three predictors can collectively account for 91% of the variance in the measured U value, with $p < 0.001$.

B. Cohens f^2

In Cohen's f^2 (Table V), the strength of the relationship of time duration, temperature difference, and wall characteristics is quite large with the measured U-value. As seen in Cohen's f^2, the strength of the relationship between time duration, temperature difference, and wall characteristics is quite significant with the measured U-value.

TABLE V. COHENS F^2 STRENGTH OF THE RELATIONSHIP

Cohens f^2	
Temperature difference 11 °C < ΔT < 15 °C	3.44
Temperature difference ΔT > 15 °C	3.47
Time Duration (hr)	3.47
Wall characteristics: The panel consisted of a four-layer wall incorporating a galvanized steel structure with a total thickness of 0.30 m.	3.47
Wall characteristics: Double-skin facade with a non-ventilated air cavity and internal insulation, finished with continuous covering, with a total thickness of 0.34 m.	3.47

C. Regression Coefficients

The following regression model (Table VI) was obtained:

- When all the independent variables are zero, the value of the measured U-value is 0.47.
- If the value of the variable temperature difference 11 °C < ΔT < 15 °C changes by one unit, the measured U-value changes by 0.02.

- If the value of the variable temperature difference ΔT > 15 °C changes by one unit, the value of the measured U-value changes by 0.02.
- If the value of the variable time duration changes by one unit, the value of the variable measured U-value does not change.
- If the value of the variable wall characteristics: Double-skin facade with a non-ventilated air cavity and internal insulation, finished with continuous covering, with a total thickness of 0.34 m changes by one unit, the value of the variable measured U-value changes by -0.24.
- If the value of the variable wall characteristics - Double-skin façade with a non-ventilated air cavity and internal insulation, finished with continuous covering, having a total thickness of 0.34m changes by one unit, the value of the variable measured U value changes by -0.16.

TABLE VI. REGRESSION COEFFICIENTS

	Unstandardized coefficients	Standardized coefficients	Standard error	t	p	95% confidence interval for B	
Model	B	Beta	Standard error	t	p	Lower bound	Upper bound
(Constant)	0.47		0.01	33.28	<.001	0.44	0.5
Temperature difference 11 < ΔT < 15	0.02	0.13	0.01	1.67	0.105	-0.01	0.05
Temperature difference ΔT > 15	0.02	0.07	0.01	1.13	0.267	-0.01	0.05
Time duration (hr)	0	0.09	0	1.76	0.089	0.0	0
Wall characteristics: The panel consisted of a four-layer wall incorporating a galvanized steel structure with a total thickness of 0.30 m.	-0.24	-1.26	0.01	-16.2	< 0.001	-0.27	-0.21
Wall characteristics: Double-skin facade with a non-ventilated air cavity and internal insulation, finished with continuous covering, with a total thickness of 0.34 m.	-0.16	-0.67	0.02	-7.47	< 0.001	-0.2	-0.11

D. Standardized Regression Coefficients

The standardized coefficient beta is independent of the measured variable and is always between -1 and 1. The more crucial the amount of beta, the greater the contribution of the respective independent variable is to explain the dependent variable's measured U-value. In this model, the variable wall characteristics are: The panel consisted of a four-layer wall incorporating a galvanized steel structure with a total thickness of 0.30 mm, which greatly influences the variable measured U-value.

E. p-Value

The calculated regression coefficients refer to the sample used for the regression analysis; therefore, it is interesting whether the individual coefficients only deviate from zero by chance or not. To test this, a null hypothesis is made for each coefficient equal to zero in the population. The standard error indicates the extent to which the respective coefficient will scatter on average when the regression analysis is calculated for a further sample. The test statistic t is calculated from the standard error and coefficient. The p-value for the coefficient of temperature difference 11 °C < ΔT < 15 °C was 0.105. Thus, the p-value is more important than the significance level of 0.05, and the null hypothesis that the coefficient of temperature difference of 11 °C < ΔT < 15 °C is zero if the population is maintained. Thus, it was assumed that the coefficient for the variable temperature difference of 11 °C < ΔT < 15 °C in the population was not different from zero.

The p-value for the coefficient of temperature difference ΔT > 15 °C was 0.267. Therefore, the p-value was greater than the significance level of 0.05, and the null hypothesis that the coefficient of temperature difference ΔT > 15 °C was zero in the population was maintained. Consequently, it is thought that the coefficient for the variable temperature difference ΔT > 15°C in the population is not different from zero. The p-value for the coefficient of time duration (hr) is 0.089 and so the p-value is greater than the significance level of 0.05. As a result, it is presumed that the coefficient for the variable time duration (hr) in the population is not different from zero. The p-value for the coefficient of wall characteristics of a panel consisted of a four-layer wall incorporating a galvanized steel structure with a total thickness of 0.30 m is < 0.001. Thus, the p-value is smaller than the significance level of 0.05, and the null hypothesis that the coefficient of this variable is zero in the population is rejected. It is therefore speculated that the coefficient for the variable wall characteristics of a panel consisted of a four-layer wall incorporating a galvanized steel structure with a total thickness of 0.30 m in the population is different from zero.

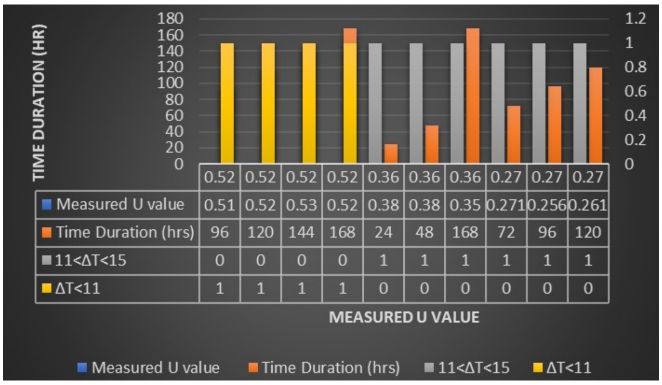

Fig. 3. Results showing the accuracy between theoretical and measured U-values of double skin facade and four-layer wall panel with air cavity and insulation in terms of time duration and temperature difference required for very low U-value walls.

The p-value for the coefficient of wall characteristics double-skin facade with a non-ventilated air cavity and internal insulation, finished with continuous covering, with a total thickness of 0.34 m is < 0.001. Thus, the p-value is smaller than the significance level of 0.05, and the null hypothesis that the coefficient of this variable is zero in the population is rejected. It is consequently estimated that the coefficient for this variable in the population, is different from zero.

V. CONCLUSION

In situ measurements have become an inevitable solution due to many parameters, such as time, dynamic effects of climatic conditions, infiltration, exfiltration, and moisture. The expected in situ behavior of the envelope is quite different from its designed, simulated, and theoretical behavior. As per standard methods, in situ measurements are limited to certain boundary conditions. This study attempts to analyze the data taken from empirical studies to illustrate the influence of the range of temperature difference, test duration, and wall characteristics on the measured U-value for low transmittance walls through a statistical analysis. It was found that there is a strong relationship between the dependent and the three independent variables. More studies should be carried out in the future to evaluate the factors influencing the results and incorporate these factors for real-time assessments of different wall characteristics.

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