Proceedings of the Canadian Society for Mechanical Engineering International Congress
32nd Annual Conference of the Computational Fluid Dynamics Society of Canada
Canadian Society of Rheology Symposium
CSME-CFDSC-CSR 2025
May 25–28, 2025, Montréal, Québec, Canada

Building Energy Estimation Through Experimental Testing and Simulation

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Abstract— Amid the growing emphasis on energy efficiency, achieving net-zero and passive house standards remains an important objective. A persistent challenge is the performance gap between simulated and actual energy consumption—underscoring the necessity for enhanced calibration of building energy modeling (BEM) software. This study employs a coupled experimental-numerical approach, integrating climatic chamber testing with BEM simulations (Design Builder) to assess two insulated building envelopes. The findings indicate a 23% to 32% performance gap, emphasizing the need for model refinement and parameter calibration to improve predictive accuracy. Addressing these discrepancies will enable more precise energy simulations and the development of high-performance, energy-efficient building envelopes suited for severe winter conditions. Furthermore, the study underscores the imperative of concurrently monitoring air-source heat pumps (ASHP) and building thermal performance, a prerequisite for ASHP integration in extreme cold climates.

Keywords-component; Co-heating; Building energy simulations; performance gap, building efficiency.

I. INTRODUCTION

Energy consumption and its optimization are critical for both economic efficiency and climate mitigation. Various sectors, including industry, power generation, and building, drive global energy demand. In 2020, the International Energy Agency (IEA) [1] reported that households in 50 surveyed countries consumed approximately 32,032 petajoules of energy. Given this significant share, research has increasingly focused on reducing and optimizing residential energy use. Pérez-Lombard et al. [2] reviewed global building energy consumption, emphasizing HVAC systems, which account for nearly 50% of building energy use. In Canada, 61.6% of residential energy is dedicated to space heating, highlighting the importance of accurate load estimation and heat pump integration. Yang et al. [3] examined thermal comfort models, concluding that adaptive models expand comfort temperature ranges, reducing cooling demand and saving energy. Cao et al. [4] analyzed global building energy trends and zero-energy building (ZEB) [5] technologies, finding that buildings consume over 40% of global primary energy. Their study identified passive design, efficient HVAC, and renewable integration as key strategies for energy reduction. Xing et al. reviewed performance gaps between predicted and measured building energy use, reporting variations from -40% to 500%, primarily due to occupant behavior, microenvironmental factors, and design discrepancies. Marshall et al. [6] investigated the thermal performance gap in a pre-1920 UK house and used Design Builder for simulation. Initially, the discrepancy was 18.5%, but adjustments reduced it to 2.4%, underscoring the need for further calibration across different building envelopes. Shi et al. [7] reviewed over 20 studies, identifying key performance gaps linked to occupancy behavior, design assumptions, and operational inefficiencies. Gao et al. [8]provided an overview of the building design process, outlining the key steps in energy modeling. Several studies have examined building performance, revealing deviations between 10% and 50%. Identifying the root causes of these discrepancies remains challenging, particularly since many investigations have not been conducted under extreme conditions. Farmer et al. [9], [10] assessed the thermal efficiency of a Victorian house model within a climatic chamber at external temperatures of 15℃, 10 ℃, and 5℃. This study employed a co-heating test to analyze the impact of various retrofit stages. The Heat Transfer Coefficient (HTC) showed a significant decline after the retrofit process, dropping from 187.5 W/K to 69.7 W/K. Additionally, simulations using Design Builder [17] and IESVE [18] were carried out to compare results, highlighting a 23.2% difference between the predicted and observed values. Furthermore, in-situ U-value measurements exhibited variations ranging from -2.3% to 28.85%. Bloem et al.[9] and Berger et al. [10] discussed experimental methods to determine the envelope performance and the associated critical parameters.

However, achieving decarbonization and net-zero buildings requires well-calibrated BEM models to optimize building parameters. While occupant behavior and equipment usage remain unpredictable, fabric performance and heating system efficiency can be accurately estimated. This study assesses building performance in a climatic chamber using a mockup of the Canadian building code [11] compliant structure retrofitted with additional insulation. A corresponding model was developed using BEM software, Design Builder, and the results were compared to identify discrepancies.

II. Methodology

This paper utilizes a unique approach, where the experimental data from the test conducted in a climatic chamber is compared with the results of BEM software. Figure 1 & 2 presents the modified methodology discussed by Gao et al. [8]. It outlines the critical input parameters for both experimental and BEM. The most significant factors are envelope characteristics, particularly U-values which are based on the local weather conditions and airtightness, contributing towards more than 60% of envelope performance [12] attributed to fabric loss—comprising mainly from conduction, convection, and radiation. While variables such as occupant behavior and equipment usage are difficult to predict, their overall contribution remains relatively minor to the envelope characteristics of a residential building.

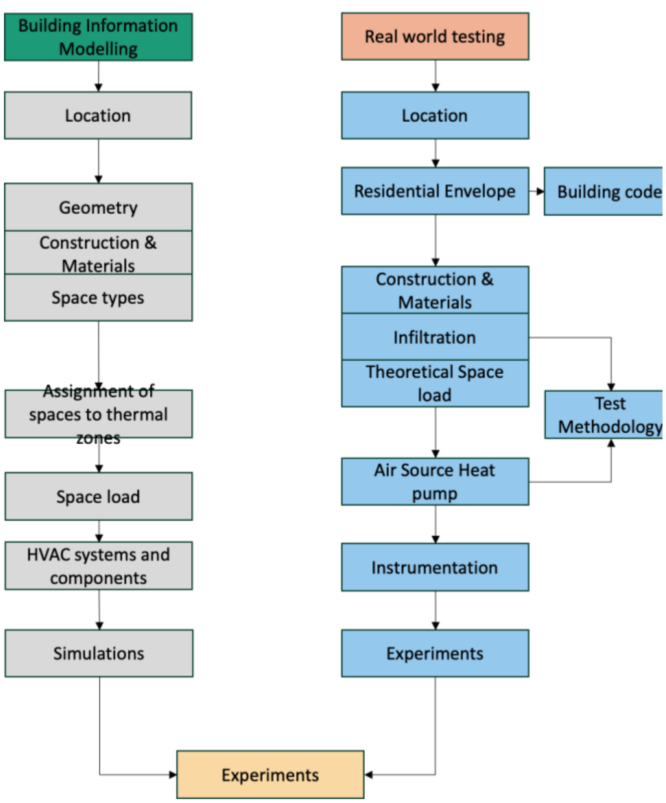

Figure 1: Methodology.

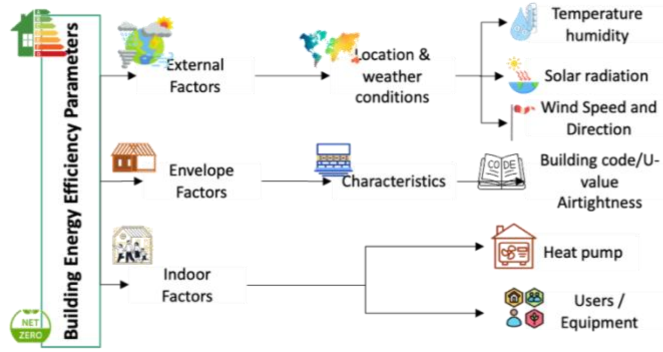

Figure 2: Parameters of building energy efficiency.

A. *Experimental Data*

Figure 3 shows the residential mockup envelope built on a trailer and tested in the climatic wind tunnel at Ontario Tech University. The envelope follows the Canadian building code and was placed on a trailer for easy mobility between test chambers and outdoor settings. While the mockup does not fully replicate a real house, it accurately predicts fabric heat loss in a controlled setting It is equipped with multiple sensors, including thermocouples, heat flux sensors, humidity sensors, and energy monitoring devices.

Before testing, a blower door test measured the air leakage at 1.46 ACH. The initial U-value was calculated using Canadian building energy code guidelines and validated with heat flux sensors. The U-Values were determined using theoretical calculations based on ISO 6946 [13] and experimentally using a simple hot box-heat flow meter principle. [14]. A commercial air-source heat pump (ASHP) was installed to maintain indoor thermal comfort. ASHP COP was also monitored to calculate the thermal output. The two envelopes were tested at 0°C, -10°C, and -25°C, representing typical conditions in climate zones 5 and 8 indicated by ASHRAE 90.1 [15]. Temperatures below -25°C were not tested due to ASHP limitations. Wind and solar radiation were excluded to ensure consistent results. The co-heating test method was used to evaluate envelope performance. Two configurations were tested separately: one following the Canadian building code referred as single stud wall (SSW) envelope and another with additional insulation on two walls to improve thermal resistance referred as mix stud envelope (MSE). The absence of solar exposure ensured accurate measurement of the envelope's thermal performance. The co-heating test method was used to evaluate two envelope types. This approach is one of the most effective for assessing the performance of a building envelope under steady-state conditions, as well as the efficiency of the heating system [16]. The co-heating test was modified to reduce the overall time as the test was performed in controlled conditions. The envelope was heated to 25°C, and once steady-state conditions were achieved, the electricity consumption of the heating equipment was measured to estimate the heat transfer coefficient. Steady-state conditions were determined based on variations in external air temperature and changes in the external wall temperatures.

Figure 3: Test building mockup envelope.

The co-heating test [17] uses an energy balance based on the whole house test method, as discussed in Equation 1, to determine the performance of the envelope using a metric called heat transfer coefficient [18].

$$\dot{Q}_{enevlope\ loss} + \dot{Q}_{ventilation\ loss} = (\Sigma U.A + 0.33N.V).\Delta T \qquad 1$$

where $\dot{Q}_{envelope\ loss}$ (W) is the sum of fabric loss, $\dot{Q}_{ventilation\ loss}$ (W) loss due to infiltration, and N is the air changes per hour (1/h). V is the volume (m^3), 0.33 is the approximate density multiplied by the specific heat capacity of air at 25℃ (kJ/m^3. K) [19], ΔT *(K)* is the internal air to external (climatic chamber) air temperature difference, U (W/m^2.K) is the thermal transmittance, and A (m^2) is the internal surface area.

The whole house energy balance can also be expressed in terms of the heat transfer coefficient, as discussed in Equation 2.

$$HTC_{electric,thermal} = \frac{\dot{Q}_{thermal}\ or\ \dot{W}_{electric}}{\Delta T} \qquad 2$$

Where $\dot{W}_{electric}(W)$ is the input electrical consumption, $\dot{Q}_{thermal}(W)$ is the output thermal energy estimated based on the coefficient of performance of the ASHP at different temperatures, and ΔT (K) is the internal air to external (climatic chamber) air temperature difference.

B. Building Energy Simulation

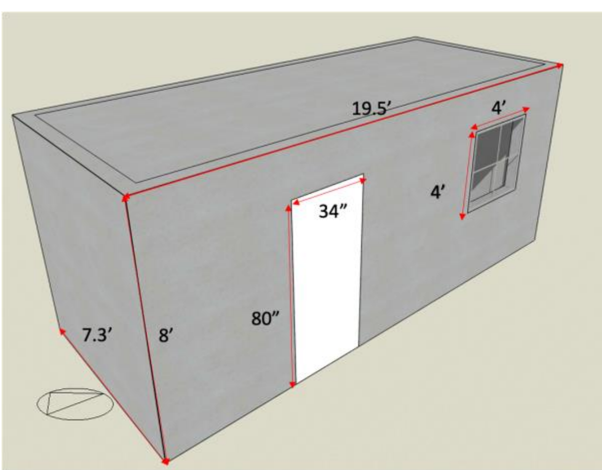

Figure 4: Simplified test building envelope model in Design Builder.

A building energy simulation software, Design Builder, was used to replicate the initial residential envelope. A detailed model was developed, ensuring the geometry and material properties closely matched those of real houses. The U-values for walls, roof, floors, and windows were set based on the physical envelope, and infiltration was set to 1.46 ACH, as determined from the blower door test. Weather conditions were sourced from Design Builder's local database, which is linked to World Meteorological Organization (WMO) data. The model was simulated under identical test conditions as the experimental setup. The first set of results was calibrated until they were closely aligned with experimental data. To ensure a valid comparison, the wall construction properties matched the actual envelope, and ambient conditions were applied. The building envelope model was simplified while maintaining the same dimensions and thermal properties as the test envelope to ensure accurate energy performance predictions

Table 1 highlights the critical parameter set on Design Builder to ensure the accuracy of the BEM model. The simulations were run for temperatures ranging from 0℃ to -25℃ and then using the heat balance from the BEM software, a relationship to the heat transfer coefficient was developed. Other parameters, i.e., external ventilation, lighting, and user, were not considered to simplify the model as much as possible. The U-values listed are based on theoretical calculations as per building code.

Table 1: Specification of two envelope type

Description (Units)	Single Stud Wall Envelope	Mix Stud Envelope
U Value Floor (W/m^2.K)	0.18	
Roof (W/m^2.K)	0.15	
Wall Type 1 (W/m^2.K)	0.14	0.27
Wall Type 2(W/m^2.K)	0.27	0.17
Window(W/m^2.K)	1.65	
Door(W/m^2.K)	0.79	
Infiltration (ach)	1.42	
Temperature ℃	25	
HVAC	Air source heat pump	
Activity	Not Defined	
Ventilation	Not Defined	

III. RESULTS

The results are divided into three sections. First, the measured U-values are discussed, followed by an analysis of the heat transfer coefficient for the single stud wall (SSW) envelope and mix stud envelope (MSE), comparing them with the BEM model predictions.

Table 2 presents the U-values of different wall types, comparing theoretical estimates, BEM predictions, and measured experimental values. The BEM model estimated lower U-values than other methods while predicting a higher energy requirement. The predicted values are based on mathematical models recommended by ASHRAE and the Canadian Energy Code.

The heat transfer coefficient calculations were initially based on measured values; however, they exhibited significant deviations. To refine the comparison, the final calculations were adjusted using BEM-estimated values.

Table 2: Comparison of U-value of BEM, measured and predicted

	U- Value (W/m^2.K)		
Wall Type	BEM	Measured	Predicted
Single Stud	0.094	0.13	0.14
Double Stud	0.2	0.22	0.28
Roof	0.15	0.15	0.16
Floor	0.13	0.16	0.17

Figure 5 presents a regression plot comparing the measured and predicted HTC using the BEM model. The measured HTC for the SSW envelope is 21.26 W/K, while the predicted value is 27 W/K, resulting in a 28% deviation. These results highlight the performance gap between the BEM model and experimental data. The regression includes a higher number of data points due to multiple steady-state simulations conducted. The number of data points in the regression is higher as more steady-state simulations were run to better fit the line. The experimental correlation has an R2 value of 0.99, which also indicates that the experiments were conducted accurately.

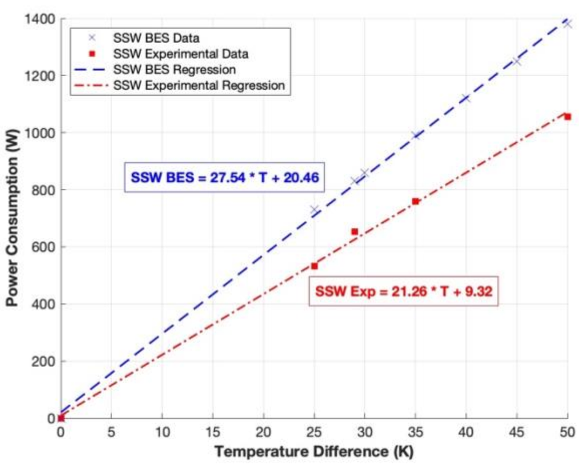

Figure 5: Comparison between measured ΔT and Q(W) during each steady state for single stud envelope type and BES model.

Figure 6 compares the average deviation of data points at similar temperatures obtained from BES and experiments. The average deviation for each data varied between 25% to 32%.

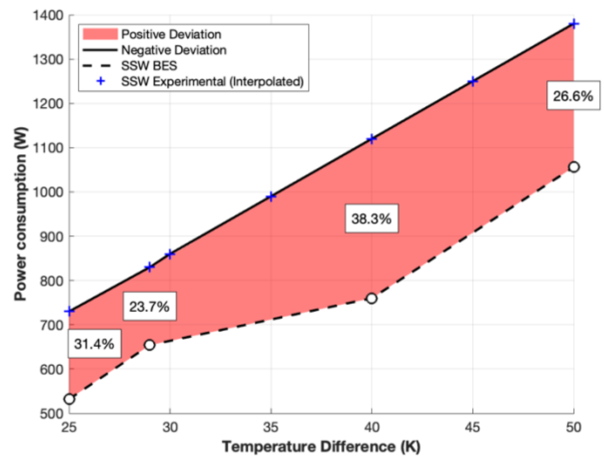

Figure 6: Percentage difference between the measured and predicted performance of a single stud envelope.

Figure 7 presents a similar regression plot to Figure 5 and estimates the HTC of mixed envelope type and BEM model. The measured HTC of MSE is 19.82 W/K and 25.14 obtained from the BEM. The deviation between the measured and predicted is 27%.

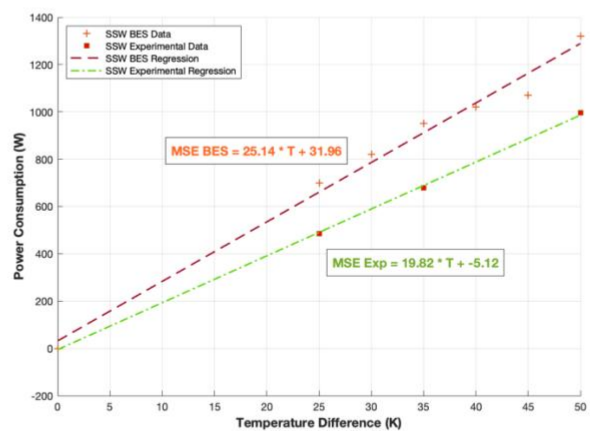

Figure 7: Comparison between measured ΔT and Q(W) during each steady state for mixed stud envelope type and BES model.

Figure 8 compares the deviation between BES and mixed stud-like estimate in Figure 6. The average deviation does not vary more than 36% and is reduced to 28% at extreme temperatures of -25℃.

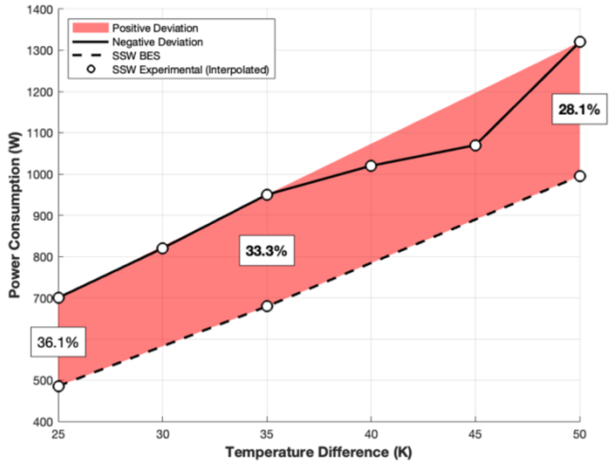

Figure 8: Percentage difference between the measured and predicted performance of mixed stud envelope.

Figure 9 presents the regression trend of input energy measured from experimental data, which, to the best of the authors' knowledge, could not be directly obtained from the BEM software. The results reveal an interesting trend: the energy required to maintain thermal comfort within the envelope remained similar until -10℃ and was slightly higher for MSE due to its greater thermal mass. However, this trend changed significantly under extreme conditions at -25℃. The SSE energy transfer was 21.05 W/K, while for MSE, it was 10.5 W/K, highlighting a significant performance variation.

This finding also underscores a limitation of BEM software when modeling air-source heat pumps (ASHP). Since ASHP performance varies with external temperature changes, most BEM approximate heating energy consumption without capturing real-time efficiency variations. To account for this, calibration with experimental data is necessary. Figure 9 compares the trend of the input electrical energy of the ASHP to maintain thermal comfort, demonstrating the impact of external temperature fluctuations on ASHP performance.

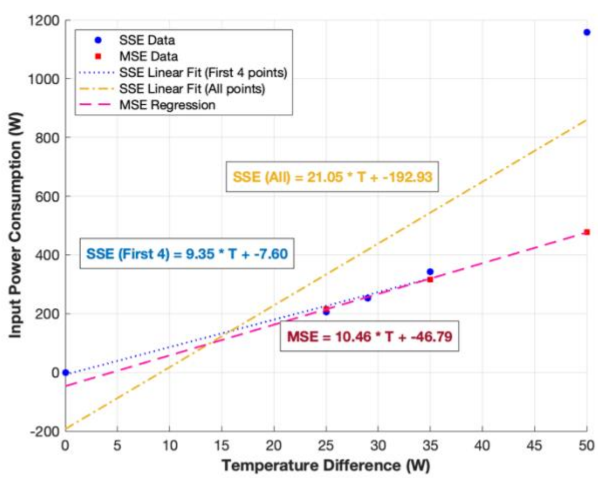

Figure 9: Relationship between input measured ΔT and Input (W) during each steady-state measurement period of SSE and MSE from experimental data.

IV. Conclusions

The paper examined the experimental and numerical studies of a mockup building envelope equipped with an air source heat pump to assess the performance gap in the building energy consumption. The experiments were conducted in a full-scale climatic wind tunnel, whereas the numerical simulation was performed using the BEM software called Design Builders. The results show a significant performance gap that remains unaccounted for, as it does not include user behavior, lighting, and other key factors. This gap mainly comes from fabric and infiltration effects. Building Energy Models (BEM) should be adjusted to reflect how Air Source Heat Pumps (ASHP) respond to changes in the microclimate, ensuring accurate sizing in extreme conditions. Lastly, insulating materials behave differently under various conditions, so energy estimates should consider more than just temperature. A correction factor should be introduced to account for these variations.

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