ARCTIC ARCHITECTURES: UNLEASHING ENERGY EFFICIENCY AND RESILIENCE IN EXTREME COLD REGIONS

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Severe cold regions like Alaska are grappling with the challenge of adapting to unpredictable temperature fluctuations and ensuring indoor thermal comfort for occupants as well as saving energy consumption of the building. Therefore, proactive measures are crucial to adapt buildings to withstand the damaging consequences of extreme weather conditions. This study focuses on the evaluation of dynamic thermal performance in wall assemblies using composite infill panels integrated into a framing system, featuring vacuum insulated panels (VIPs). A precast residential unit located in Alaska serves as the testing ground. A comprehensive dataset collected by the Cold Climate Housing Research Center (CCHRC) from January to April 2023 in Fairbanks, AK Leveraging, including outdoor and indoor temperature, heat flux, and relative humidity measurements is utilized. The evaluation of the wall panels' dynamic thermal performance is conducted by using two key metrics of Decrement Factor (DF) and Time Lag (TL). Additionally, the study examines the correlation between temperature fluctuations, heat flux, and relative humidity. The results reveal a direct correlation between temperature fluctuations during winter conditions and heat flux, while relative humidity demonstrates an inverse correlation. This research contributes to the development of energy-efficient and resilient buildings in Arctic regions. These insights will aid decision-makers in effectively adapting to the challenges posed by extreme weather conditions associated with climate change. Ultimately, this study paves the way for the creation of buildings that can thrive in severe cold climates while ensuring optimal energy efficiency and occupant well-being.

Keywords: Decrement factor, Time lag, Building envelope, Sustainable and resilient construction, Wall panels.

1 INTRODUCTION

In 2022, the residential and commercial sectors accounted for approximately 22 quadrillion British thermal units (BTU) of combined end-use energy consumption, which constituted approximately 29% of the total US end-use energy consumption for the same year (US EIA 2023). In regions characterized by harsh climatic conditions such as Alaska, a significant proportion of energy consumption and resulting environmental pollution is attributed to the heating of residential buildings (Ozel 2013). As an example of utilizing passive measures for building envelopes, the implementation of a greening system – aimed at enhancing energy efficiency and achieving indoor thermal comfort by covering vegetation on walls to help absorb rainwater and improve thermal insulation performance – can be mentioned which is able to effectively mitigate up to 50% of the air-conditioning load and provides improved indoor thermal comfort by mitigating solar energy
penetration through the building envelopes (e.g., walls and windows) (Wong et al. 2009, Li and Wen 2021). The significant temperature fluctuations experienced in cold climates have a notable impact on buildings and occupants (Aghniaey and Lawrence 2018). These temperature variations can pose challenges in terms of thermal comfort, energy efficiency, and structural integrity. Occupants may also experience discomfort and health risks. Therefore, evaluating the thermal performance of building envelope systems is very crucial to measure the resiliency of building design and envelope components and enhance their adaptability to cope with extreme and unpredictable temperature fluctuations in cold climates.

The objective of this study is to evaluate the dynamic thermal performance of walls in extreme cold regions. To achieve this, dynamic thermal properties of wall panels of a precast residential unit of was evaluated to assess their resiliency and adaptability to cold climates. The evaluated wall panels consist of composite infill panels integrated into a framing system with vacuum insulated panels (VIPs). The dynamic thermal performance evaluation of the wall panels utilizes a comprehensive dataset collected by the Cold Climate Housing Research Center (CCHRC) during the period of January to April 2023 in Fairbanks/AK. The dataset encompasses measurements of outdoor and indoor temperature, heat flux, and relative humidity. Dynamic thermal performance was measured with two properties: (i) TL refers to the delay between the peak outdoor surface temperature and the peak indoor surface temperature, and (ii) DF refers to the decreasing ratio of the heat wave amplitude from outdoor to indoor environment (Asan 2006). The existing body of literature on the thermal performance of walls envelopes predominantly concentrates addressing extreme temperatures in the hot climates, while investigations into the impact of winter conditions on such systems are comparatively limited (Nan et al. 2020). Most of the current research has focused on assessing the thermal performance of buildings using numerical and simulation methods, which may not accurately represent real-world conditions (Mazzeo et al. 2016, Balaji et al. 2019).

2 LITERATURE REVIEW

Previous research studies have focused on investigating the impact of thickness, orientation, and types of insulation materials used in exterior walls on thermal performance in extreme cold conditions. Aksoy (2012) and Ozel (2013) investigated the impact of orientation and thickness of wall panels on buildings thermal performance in cold climate conditions. Aksoy (2012) studied on five different types of walls on energy savings in Elazığ (i.e., one of the coldest regions in Turkey) through a simulation-based study. The results indicated a reduction in energy consumption ranging from 19% to 78% when varying the insulation thickness between 2.5cm and 15cm. Ozel (2013) found out that orientation of building wall greatly impacted TL, but only has a minor effect on DF values. As the insulation thickness increases, DF decreases, and TL increases. Baglivo and Congedo (2016) presented a method based on a multi-criteria analysis for the design of energy-efficient precast walls in cold climate of Balzano/Italy. It has been demonstrated that precast walls can achieve high efficiency even when made with thin or ultra-thin thicknesses. Klöseiko et al. (2015) conducted in-situ tests on internal insulation in a historical building for nine months in a cold region in Estonia. Their evaluation of four insulation materials (CaSi, AAC, IQ-T, and PIR) involved monitoring temperatures, heat flows, and relative humidity to determine their hygrothermal performance when applied to a brick wall from the inside. All cases had higher temperatures than the reference wall and improved thermal comfort. The temperature inside rose and thermal transmittance decreased by half in most cases. It was also discovered that built-in moisture during installation can cause interstitial condensation in walls due to high relative humidity.
3 OBJECTIVE

The objective of this study is to evaluate the dynamic thermal performance of precast residential unit walls in the winter season in Fairbanks, Alaska. Accordingly, dynamic thermal properties (e.g., DF and TL) were determined to assess their resiliency and adaptability to extreme cold climates.

4 METHODOLOGY

Numerous studies have examined the dynamic thermal of building envelopes through different approaches, including numerical and experimental analyses, to determine the DF and TL values under sinusoidal and non-sinusoidal outdoor temperature simulations (Jin et al. 2012, Mazzeo et al. 2016, Fathipour and Hadidi 2017, Balaji et al. 2019). DF and TL play a crucial role in assessing the thermal characteristics of a building. They are instrumental in evaluating thermal comfort and energy efficiency, thereby providing valuable insights for the design and optimization of building envelopes (Jin et al. 2012, Gagliano et al. 2014). The decrement factor refers to the ratio by which the amplitude of heat waves decreases from the exterior to the interior surface of a wall panel. Additionally, the time lag represents the duration it takes for the heat wave to propagate from the outer surface to the inner surface of the wall (Asan 2006). In general, a higher TL and a lower DF lead to reduced fluctuations in indoor temperature, thereby improving the overall thermal comfort for occupants (Fathipour and Hadidi 2017, Yang et al. 2018).

The aim of this study is to evaluate the dynamic thermal behavior of the wall panels of a precast residential unit during the winter season in Fairbanks, Alaska, considering real-time outdoor temperature conditions. This is accomplished in three steps. First, weather dataset was extracted from CCHRC website (CCHRC 2023) that includes several variables such as outdoor and indoor air and surface temperature, heat flux, and relative humidity obtained from January 14 to April 10, 2023, in Fairbank/AK. Heat flux sensors and temperature-recording sensors collected data in three sections of the wall's interior and exterior surfaces, therefore average is taken from the three parts. Second, hourly data are categorized for a day-wise analysis to calculate the DF and TL values. Moreover, the average air temperature is collected from the roof weather station on the CCHC website for comparing local temperature with outdoor surface temperature. Third, DF and TL are calculated in two phases: (i) Tuning phase that allows two-weeks (14 days) extreme temperature exposure to the extreme winter season to adjust the wall sample to the extreme weather condition, (ii) Actual phase that allows continuation of remaining of dataset (73 days) to evaluate the dynamic thermal performance of walls by calculating TL and DF values.

5 RESULTS AND DISCUSSION

Figure 1 illustrates the daily DF values revealing a gradual decrease over time. During the tuning phase, the DF values were notably higher compared to the actual phase of 73 days. The average DF during the tuning phase was determined as 0.11, while the average DF for the remaining DF values was 0.06.

Figure 2 presents the temperature variations in indoor and outdoor environment from January 14 to April 10. The day of March 24 is magnified to depict the TL values of 5 h for both crest (TLc) and sag (TLs). These values during the tuning phase calculated as 3.79 h and 3.14 h, respectively. TLc and TLs values for the remaining 73 days are 4.91 h and 4.14 h, respectively. The higher TL and lower values of DF after the tuning phase indicate that the wall sample exhibited a responsive behavior towards temperature fluctuations. This implies that the tested wall effectively adapted to the extreme cold conditions within a period of the tuning phase. Moreover, the results show the highest air temperature in Fairbanks/Alaska in the study period is around 6.5°C (43.7°F), and the
coldest recorded temperature is approximately -31.2°C (-24.2°F), while the indoor surface temperature range is between 13.4°C (56.1°F) to 20°C (68°F) which shows the tested wall panel performs well in controlling heat transfer from outdoor to indoor environment under extreme cold weather conditions.

In this study, data on heat flux and relative humidity are collected to examine the correlation between these variables in conjunction with outdoor temperature variations (Figure 3). The average heat flux data for every 24 hours is depicted in Figure 3a. As temperature rises, there is a corresponding increase in heat flux due to their direct correlation. On the other hand, humidity and temperature exhibit an inverse correlation. With higher temperatures, there is a tendency for increased moisture retention until the point of saturation. Conversely, a decrease in temperature leads to higher relative humidity. It is observed that there is a peak in relative humidity at 38% when the air temperature was approximately -27°C (-16.6°F) (see Figure 3b). It is important to acknowledge that this relationship is not always straightforward, as other factors like air velocity, surface emissivity, and material properties can also influence the rate of heat transfer significantly. As a result, the correlation between heat flux and relative humidity can exhibit significant variability and dependency on specific circumstances.
6 CONCLUSION

The dynamic thermal performance of building envelopes is significantly dependent on drastic temperature fluctuations having a substantial impact on energy consumption as well as the thermal comfort of occupants. In this paper, the dynamic thermal performance of a precast residential unit in Fairbanks/Alaska is investigated by measuring its DF and TL values. The correlation between temperature fluctuations, heat flux, and relative humidity is assessed. A comprehensive dataset, including outdoor and indoor surface and air temperature, heat flux, and relative humidity collected by CCHRC is used. According to the dataset the studied location experienced a maximum air temperature of 6.5°C (43.7°F) and a minimum temperature of -31.2°C (-24.2°F) from January 14 to April 10, and the indoor surface temperature varied between 13.4°C (56.1°F) and 20°C (68°F), indicating effective heat transfer control by the tested wall panel due to maintaining a stable indoor temperature (i.e., low DF of 0.06 and high TL of 4.91 h). It is seen that the heat flux is directly related to temperature and increases as temperature rises. Furthermore, the air moisture capacity increases with higher temperatures, creating an inverse relationship between humidity and temperature. The relative humidity reached a maximum of 38% when the air temperature was near -27°C (-16.6°F). Higher relative humidity levels lead to decreased heat flux because of lower temperature differences and more moisture in the air, which hinders heat transfer. Given the limited investigations into the dynamic thermal behavior of building envelopes under extreme cold conditions, this study can serve as a preliminary endeavor to initiate and pave the way for future research in this field.

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References


