Mold Growth Affecting the Achievement of NZEB in the Long Term in Tropical Climates

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Abstract

The net-zero energy concept significantly impacts global goals regarding energy accessibility (SDG 7) and responsible consumption (SDG 12), particularly in the building sector, which accounts for substantial energy use and greenhouse gas emissions. While extensive research on Net Zero Energy Buildings (NZEB) has focused on the global north, tropical regions require further study, where high solar radiation, temperatures, and humidity challenge building performance throughout the year. Addressing problems like mold growth caused by these tropical climate aspects can undermine NZEB's performance. This study aims to evaluate the impact of mold growth on a representative building under the tropical climate of Panama City (high temperatures and humidity) and Boquete (low temperatures and high humidity). Long-term hygrothermal and energy performance analyses are conducted using simulation software to assess when and how mold growth affects building performance. Mold can harm the health of occupants and increase energy consumption, as additional humidity control devices may be required after the building's design phase.

1. Introduction

Reducing building energy consumption is among the actions outlined to address the 2030 Agenda Sustainable Development Goals and cut global emissions. Current energy policies encourage airtight and highly insulated building envelopes to achieve Net Zero Energy Buildings (NZEB). As a result, NZEB often has insufficient indoor air exchanges, which reduce air quality and produce higher latent loads. High indoor humidity and the increasing tendency to use organic building materials facilitate the growth and spread of mold in indoor environments (Brambilla & Sangiorgio, 2020). The combination of factors such as humidity, temperature, exposure time, and nutrient availability leads to the growth of fungi on internal surfaces (Di Giuseppe, 2013). Prolonged exposure to relative humidity above 80% and temperature between 15 and 30 °C indicates a high risk of mold growth. The risk is also intensified by increased capillary water absorption (Parracha et al., 2024). In particular, moisture condensation is more likely to occur at wall corners, vertical wall connections, and ceiling joints (You et al., 2017) and depends on the wall orientation (Xue et al., 2022). Mold growth can cause degradation of construction materials and poor indoor air quality, impacting respiratory health with respiratory problems such as asthma or allergic rhinitis and occupant discomfort (Hall et al., 2013). It is recognized that fungal colonization in indoor environments is an important public health problem, and currently, no regulation or threshold value for the intensity of fungal colonization has been agreed upon internationally, partly due to the lack of quantitative studies that connect intensities directly to adverse health effects (Perez et al., 2024). The rise in temperature and humidity due to climate change even exacerbates the problem (Zhao et al., 2024).

The renovation of buildings with the addition of thermal insulation can promote the growth of fungi. (Recart & Sturts Dossick, 2022) observed that post-retrofit of buildings' envelopes may experience higher levels of moisture and dampness, increased condensation risk, and more rapid structural deterioration due to higher humidity levels. (Liu et al., 2024) and (Hall et al., 2013) also reported an in-

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creased occurrence of mold growth conditions following thermal insulation, particularly in humid climates (Silveira et al., 2019). The phenomenon is more pronounced in low-energy buildings (Carpino et al., 2023), in which high levels of Volatile Organic Compounds have been found (De Jonge & Laverge, 2021) (Yang et al., 2020) and in near-zero energy, where internal microbial contamination was detected (Kang & Nagano, 2016) (Sharpe et al., 2016). Considering NZEB characteristics, humidity control is essential to prevent health hazards associated with moisture and mold growth (Tang et al., 2020). (Qiao et al., 2024) proved that relative humidity lower than 75 % at a temperature of 25 °C represents safe conditions for mold formation in all the ten different building materials analyzed. Therefore, moisture safety should be included in the commissioning process for renovation in nearly zero-energy buildings to ensure sustainability and high-quality interventions (Pihelo & Kalamees, 2021). Effective measures to prevent moisture-related risks include predicting the mold index (Aggarwal et al., 2024), monitoring thermo-hygrometric conditions during the building's operation (Fedorik et al., 2021) (Shaw et al., 2024), using moisture-regulating materials (Verma, et al., 2022) (Kumar et al., 2023) and bio-based materials (Tlaiji et al., 2022) (Jirgensone et al., 2024).

Furthermore, ventilation is essential in maintaining appropriate indoor conditions (Niculita-Hirzel et al., 2020), as well as the filter efficiency when using mechanical ventilation (Pavard et al., 2022).

Few studies have been conducted on the risk of fungal growth in Zero Energy Buildings in tropical climates. (Strang et al., 2021) investigated the durability of envelopes made with mass timber in the hot and humid climate of Australia, emphasizing the best practice of informing the design process with hygrothermal risk and mold growth assessments. (Udawattha et al., 2018) have studied the growth of moss and mold on walls of different materials in tropical climate, showing that high porosity and high organic content promote the colonization and proliferation of fungi.

Therefore, the objective of the present study is to assess the risk of mold growth in an NZEB building in a tropical climate and evaluate how the need to dehumidify spaces to reduce the risk of condensation and, thus, fungal growth can impact energy consumption and the maintenance of NZEB performance during the building's operation.

2. Simulation

2.1 Methodology

The study is based on analyzing a building renovated to become NZEB in a tropical climate following conventional methodology, according to the energy efficiency measures explained in the previous study (Carpino et al., 2024). The renovation of the building, which required energy upgrading of the building envelope, increased cooling system efficiency, and integration of renewable sources, resulted in a Net Site energy balance close to zero, thus achieving an NZEB. The next phase, addressed in the present study, involves investigating the behavior of the building during its operation. Specifically, indoor temperature and relative humidity levels are analyzed in order to detect the occurrence of conditions favorable to mold growth. The need to control humidity could lead to an increase in energy demand, shifting the building away from the NZEB target. The methodology was developed in three phases. First, the entire building model was created in DesignBuilder to simulate the indoor climate (air temperature and relative humidity) of each room. In the second phase, using the WUFI Pro software, a dynamic hygrothermal analysis was conducted for the external walls of two different rooms, representative of two indoor conditions (air-conditioned and not air-conditioned rooms). Finally, the WUFI Bio postprocessor was launched directly, acquiring the dynamic thermohygrometric analysis results to assess the mold formation risk. The influence of climate was considered by simulating the building in two different locations: Panama City, which is characterized by high temperatures and humidity, and Boquete, which has low temperatures and high humidity, both in Panama.

2.2 Description of the Case Study

The case study consists of a single-family residential building with a total enclosed area of 65.80 m^2. The dwelling is single-story and includes ten zones. The image in Fig. 1 depicts the floor plan of the house.

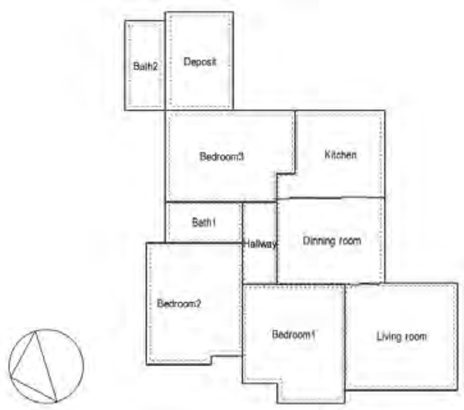

Fig. 1 – Floor plan of the analyzed single-family house

Following the renovation, the building was converted into a NZEB. Table 1 shows the characteristics of the building elements after refurbishment. Fixed solar shading consisting of horizontal overhangs is applied to windows. Only three rooms are equipped with a cooling system. The latter corresponds to split units with an average seasonal efficiency (CoP) of 3.0 and operating on a schedule from 11 p.m. to 7 a.m., with a set-point temperature of 28 °C. This operation was defined as the NZEB's optimum point, identified through a multi-objective optimization procedure, shown in the paper (Carpino et al., 2024), which also complies with national regulations.

Table 1 – Optimal U-values for the building elements

Building elements	Optimal U-value [W/m²K]
External walls	2.2
Roof	0.4
Ground floor slab	3.8
Semi-exposed ceiling	4.0
Windows	3.0

Air dehumidification is active in the rooms with a cooling system, with a set-point of 60 %. No air exchange between rooms is modeled. A 3 kWp photovoltaic system is installed on the roof of the building. The building, as renovated, has an energy demand of 52.80 kWh/m²y in Panama City and 40.46 kWh/m²y in Boquete. Considering the PV producibility, the building shows an energy surplus of 936.64 kWh/y if located in Panama City and 1984.38 kWh/y if located in Boquete, thus performing as an NZEB.

2.3 Mould Growth Risk Assessment

Considering the building during the operation phase, hourly simulations were conducted in DesignBuilder in both locations to investigate the evolution of indoor conditions. The graph in Fig. 2 shows the air temperature and relative humidity of the living room, which was not equipped with cooling and dehumidification, for Panama City for one year. It can be seen that the relative humidity often reaches high values (over 80 %).

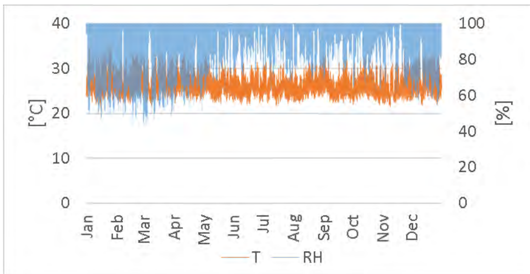

Fig. 2 – Hourly trend of indoor air temperature and relative humidity of the living room (no cooling and dehumidification) for Panama City

Subsequently, using WUFI Pro, dynamic thermo-hygrometric analysis was conducted for the external walls of two rooms: Bedroom 2, equipped with air conditioning, and the Living Room, without air conditioning. WUFI Pro allows for the calculation of heat and moisture fluxes through a building component exposed to certain outdoor and indoor climatic conditions. Specifically, the following climatic conditions were adopted. The same ".epw" file used in DesignBuilder was provided for the outdoor climate. For indoor climate, the "sinusoidal" modeling option was selected. This allows the indoor climate to be modeled as a sine wave of an annual period based on user-defined data. Specifically, by providing the average values of room temperature and relative humidity (obtained from the DesignBuilder simulation) and the amplitude of the quantities, thus the variability between the minimum and maximum values, the software outlines a sinusoidal trend for the indoor climate in terms of indoor temperature and relative humidity. Based on the ambient data, the program performs transient thermo-hygrometric simulations through the various layers of the building component.

As shown in Fig. 3, the south wall of the living room is affected by surface condensation because the surface temperature reaches the dew point. This seems to create suitable conditions for mold development. Therefore, the risk of mold growth was assessed using the WUFI Bio software. This post processor can be launched directly from inside the WUFI Pro, being integrated into it, and is able to acquire the results of the simulation carried out by WUFI Pro (computed hourly temperatures and relative humidity at the interior surface of the component).

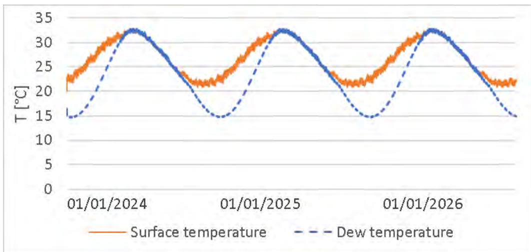

Fig. 3 – Trend of the surface temperature and dew temperature for the south wall of the living room (Panama City)

WUFI Bio uses the biohygrothermal model to assess the risk of mold growth under transient ambient conditions. This method is based on comparing the simulated (or measured) transient ambient conditions and the growth conditions needed by the fungi usually encountered in buildings. The moisture content of the mold spores is simulated and compared with the critical content required for spore germination. Once germination has occurred, growth curves are used to estimate the subsequent spread of the infestation. The results regarding mold growth rate (mm/year) are provided and associated with different occupant exposure classes. Moreover, according to the approach developed by (Viitanen et al., 2015), the software allows the conversion of the "mold growth" determined by WUFI Bio's biohygrothermal model into the "mold index" used by the Viitanen model. The model provides three classes of occupant exposure and different levels of severity of mold infestation if present on indoor air contact surfaces. A class labeled "green traffic light," indicates mold growth < 129 mm/year and a mold index ≤ 1. A class labeled with the "yellow traffic light" has mold growth between 129 and 176 mm/year and a mold index between 1 and 2. Finally, a class labeled "red traffic light" is obtained for mold growth > 176 mm/year and mold index > 2. The analysis conducted for the south wall of the living room returns the "red light signal" for mold risk for both locations analyzed. Specifically, the mold index equals 6, and the mold growth rate is greater than 176 mm/year in both cases. This level is usually considered unacceptable. The graphs in Fig. 4 and Fig. 5 show the critical water content and the spore's water content evaluated for the south wall of the living room in Panama City and Boquete, respectively.

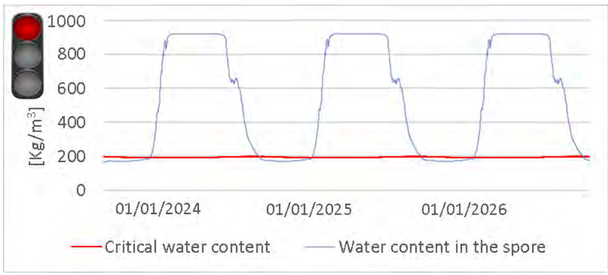

Fig. 4 – Critical water content and water content in the spore evaluated for the south wall of the living room (Panama City)

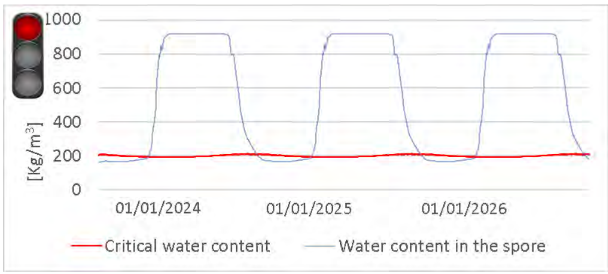

Fig. 5 – Critical water content and water content in the spore evaluated for the south wall of the living room (Boquete)

The analysis conducted for the north wall of Bedroom 2, equipped with a cooling and dehumidification system, returns the "green light signal" for both locations. The water content in the spore decreases, as illustrated in Fig. 6 and Fig. 7, corresponding to the two different locations. The mold index is 0.87 for Panama City and 0.056 for Boquete. This level is usually considered "acceptable."

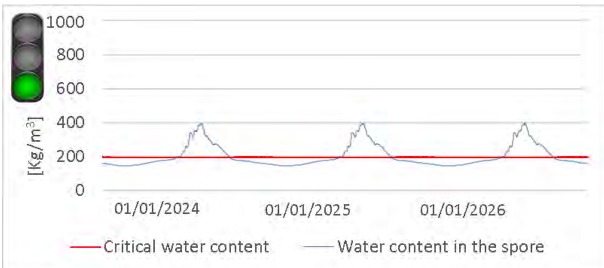

Fig. 6 – Critical water content and water content in the spore evaluated for the north wall of the bedroom (Panama City)

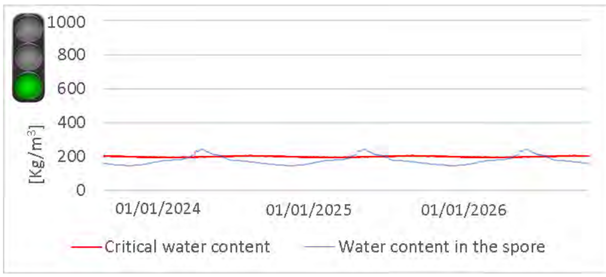

Fig. 7 – Critical water content and water content in the spore evaluated for the north wall of the bedroom (Boquete)

However, when the water content in the spore exceeds the critical water content, it is assumed that the spore can germinate, and fungal growth can develop. In the long run, this can damage surfaces and pose a threat to the health of occupants. Fig. 8 shows the mold growth rate over three years for the north wall of bedroom 2 for the building located in Boquete. Although the mold risk classification returns a green light, which is considered an acceptable level, in the long period, with the interior conditions remaining unchanged, mold progressively grows.

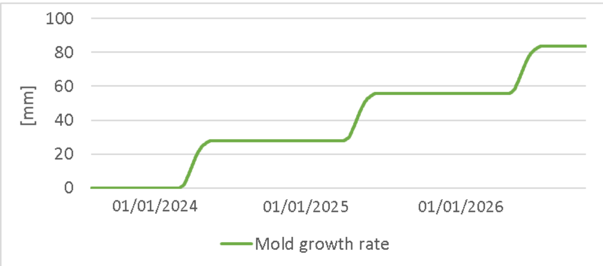

Fig. 8 – Mold growth rate for the north wall of the bedroom (Boquete)

3. Discussion and Result Analysis

The findings presented underscore the crucial role of mold risk prevention measures and their impact on energy consumption. The ideal condition necessitates that mold does not grow on interior surfaces. Therefore, to mitigate the risk of mold, humidity control and cooling must be extended to all rooms in the house. In the case of the Panama City building, to eliminate the mold risk, in addition to extending cooling to the whole house, the cooling set-point temperature must also be lowered from 28 °C to 26 °C.

Under these conditions, the simulations showed zero risk of mold formation. It is worth noting that although lowering the temperature leads to an increase in relative humidity, the extension of humidity control in all areas ensures safety from mold risk. However, this results in an increase in energy consumption by about 46 %. The total energy demand rises from 52.80 kWh/m²y to 77.30 kWh/m²y, and the Net Site energy balance passes from -936.64 kWh/y (surplus of renewable) to 674.75 kWh/y (withdrawn from the grid). This means that the building designed to be an NZEB, under operating conditions, with the intent to ensure mold safety and the well-being and health of the occupants, will have higher energy consumption. Consequently, the NZEB target is nullified.

Regarding the building located in Boquete, it is sufficient to extend the humidity control to 60 % for the whole house, maintaining a set-point temperature of 28 °C. Simulations conducted under these conditions have shown the absence of mold formation. However, an increase in energy consumption is also recorded in this case. The energy demand increases from 40.50 kWh/m²y to 42.50 kWh/m²y. The Net Site energy balance passes from -1984.38 kWh/y to -1849.80 kWh/y. In this case, even after implementing mold risk prevention measures, the building remains an NZEB, albeit with an increase in energy demand of about 5 %. This trade-off between mold prevention and energy consumption highlights the challenges of maintaining a balance between occupant health and energy efficiency. The graphs in Figures 9, 10, and 11 display monthly energy consumption trends and Net Site energy balance under design conditions and operating conditions to prevent fungal growth in the two locations.

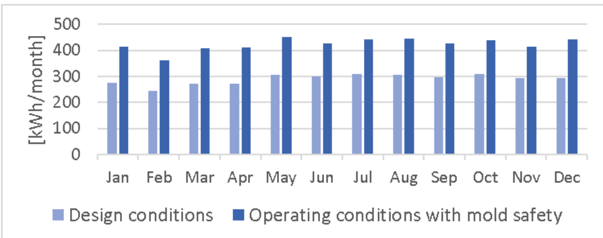

Fig. 9 – Monthly energy consumption under design and operating conditions with preventive measures for mold safety, Panama City

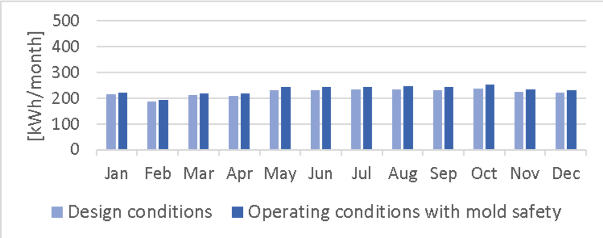

Fig. 10 – Monthly energy consumption under design and operating conditions with preventive measures for mold safety, Boquete

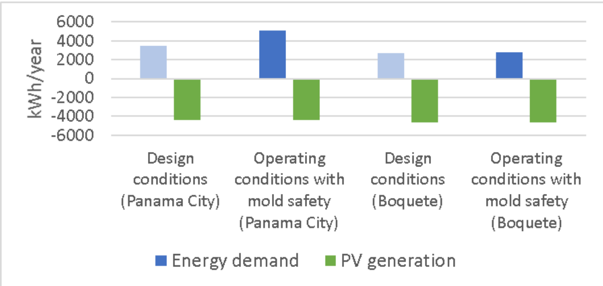

Fig. 11 – Annual Net Site energy balance under design conditions and operating conditions with mold safety for the two locations

4. Conclusion

The present study analyzed the performance of a renovated NZEB building in a tropical climate. A single-family house was considered, located alternately in Panama City and Boquete (Panama). The results of simulations conducted in DesignBuilder and WUFI showed that there is a mold growth risk during building operation. In particular, an occupant exposure Class III (red light) was found for non-air-conditioned areas, in which high indoor humidity is achieved along with high temperature. Under these conditions, mold growth and proliferation become a severe risk for occupants.

In order to prevent microbiological contamination, it is necessary to dehumidify the indoor environment. Dehumidification comes as the only effective measure since ventilation is not useful in lowering humidity levels in hot and humid climates. The application of dehumidification and, therefore, cooling to all the rooms of the house and for the whole day results in significant increases in energy consumption. The increase in energy demand is such that the NZEB behavior is nullified for the building located in Panama City, while for the building located in Boquete, the NZEB target is maintained despite an increase of 5 % recorded. The obtained results, therefore, suggest that special attention should be paid to indoor mold risk assessments when designing NZEB in tropical climates.

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