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Research Article

Mold development risk assessment in the inner side of a building envelope under varying climate conditions

Bahar TÜRK*

Department of Interior Architecture and Environmental Design, Beykent University Faculty of Fine Arts, İstanbul, Türkiye

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ABSTRACT

Mold infestation in buildings can arise due to favorable growth conditions for mold fungi, posing significant health risks and structural damage. This research aims to understand the complex transient building physics processes influencing mold development, focusing on the influence of physical building variables on the transient humidity and temperature behavior of building components in various climates. The study utilizes WUFI, a hydro-thermal simulation software, to assess mold risk in an exterior wall design. The results indicate that a broadly applicable approach can effectively guide safe design practices. The goal is to predict mold development on building materials during the design stage and minimize the risk of mold growth throughout the materials' service life.

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INTRODUCTION

Mold growth in buildings is a pressing issue that has garnered considerable attention due to its adverse effects on both human health and structural integrity. Mold can trigger respiratory problems, allergic reactions, and other health issues in occupants. Moreover, it can lead to significant structural damage, compromising the safety and longevity of buildings. Understanding the conditions that foster mold growth is paramount for developing effective prevention strategies, particularly in the context of varying climatic conditions [1–3].

Importance of Mold Prevention

The inner side of building envelopes, being less visible and often overlooked, can become a hotspot for mold growth if not adequately managed. Factors such as high relative humidity, fluctuating temperatures, and prolonged exposure to moisture can create an ideal environment for mold proliferation [4, 5]. To address this, building scientists and engineers must consider these variables during the design and construction phases [6, 7].

Objectivesof The Study

This study aims to extend the knowledge on mold development risk by:

1. Assessing the influence of physical building variables on the transient humidity and temperature behavior of building components in various climates.
2. Using WUFI to simulate an exterior wall design and evaluate mold growth risk.
3. Providing insights that can guide the design phase to minimize the risk of mold growth over the service life of building materials.

Significance

The outcomes of this research are anticipated to make a substantial contribution to the field of building science by offering a widely applicable method for assessing mold risk.

***Corresponding author.**
*E-mail address: bahareturk@gmail.com

This methodology can aid designers and builders in developing safer, more durable structures by integrating mold prevention strategies from the initial design phase [8, 9].

Theoretical Framework

This study's theoretical approach is based on building physics principles, with an emphasis on the complex interactions of heat and moisture movement within building envelopes. Understanding these interactions is critical for forecasting and restricting mold growth, which is affected by several major factors: relative humidity, temperature, and time exposure [10, 11].

Heat and Moisture Transfer

Understanding the interactions between heat and moisture within building envelopes is essential for predicting and mitigating mold growth. Several key processes govern the movement of heat and moisture through building materials, each contributing to the overall behavior of the building envelope under different environmental conditions. The main processes include conduction, convection, radiation, diffusion, and capillarity [12, 13].

Conduction

Conduction is the process by which heat energy is transferred through a material due to a temperature gradient. In the context of building envelopes, conduction occurs through the walls, floors, and roofs as heat moves from the warmer side to the cooler side. The rate of heat transfer by conduction depends on the thermal conductivity of the materials involved and the temperature difference across them [14].

Materials with high thermal conductivity, like metals, transfer heat more efficiently than insulating materials. The thickness of the material also affects the rate of heat transfer; thicker materials slow down conduction [15, 16].

Convection

Convection involves the transfer of heat and moisture through the movement of air. This process can occur within the air spaces of a building envelope or on the surface of building materials. There are two types of convection: natural convection, driven by temperature differences causing air movement, and forced convection, driven by external forces such as fans or wind [17].

Natural convection occurs due to buoyancy effects where warmer, less dense air rises and cooler, denser air sinks. Forced convection is enhanced by mechanical means like HVAC systems. Convection can contribute to heat loss or gain and influence moisture levels in building cavities [18, 19].

Radiation

Radiation is the transfer of heat in the form of electromagnetic waves, primarily infrared radiation. Unlike conduction and convection, radiation does not require a medium to transfer heat. In buildings, radiation can occur through windows, roofs, and walls exposed to the sun or other heat sources [20].

All objects emit and absorb radiant energy. The amount of radiation emitted depends on the temperature and surface properties of the material.Reflective surfaces can reduce radiant heat transfer by reflecting incident energy [21, 22].

Diffusion

Diffusion refers to the movement of moisture (water vapor) through building materials due to vapor pressure differences. This process is critical in understanding how moisture migrates through walls, roofs, and floors, and how it can lead to condensation and mold growth [23].

Moisture moves from areas of high vapor pressure to areas of low vapor pressure. Vapor permeability of materials dictates how easily moisture can diffuse through them. Proper vapor barriers can control diffusion and prevent moisture buildup within the building envelope [24, 25].

Capillarity

Capillarity, or capillary action, is the movement of liquid moisture through porous materials due to the forces of adhesion, cohesion, and surface tension. This process is significant in porous building materials like concrete, brick, and wood, where moisture can travel upwards against gravity [26].

Capillary action can transport moisture from the ground into walls and floors.

The size and connectivity of pores in a material influence the rate and extent of capillary rise. Proper detailing and use of damp-proof courses can mitigate capillary moisture intrusion [27, 28].

Relative Humidity

Relative humidity (RH) is a critical factor in mold development. It is defined as the amount of moisture in the air relative to the maximum amount the air can hold at a given temperature. High RH levels can lead to condensation on building surfaces, creating an environment conducive to mold growth. Laboratory tests have established threshold values for RH above which mold is likely to develop [29]. Effective moisture control strategies aim to maintain indoor RH levels below these critical thresholds [30].

Table 1 categorizes the risk levels for mold growth based on relative humidity percentages. Maintaining RH below 60% is considered safe, while levels above 80% significantly increase the risk of mold development.

Temperature

Temperature plays a significant role in both the rate of mold growth and the moisture dynamics within building materials. Warmer temperatures can accelerate mold growth by providing favorable conditions for spore germination and proliferation. Conversely, cooler temperatures can slow down mold growth but do not eliminate the risk entirely [31]. Temperature also affects the vapor pressure and, consequently, the diffusion of moisture through building materials [32].

Table 1. Mold growth risk based on relative humidity

Condition	Relative humidity (%)
Safe zone	<60
Risk zone	60–80
Critical zone	>80

Table 2. Temperature Influence on mold growth rate

Temperature (°C)	Mold growth rate
0–10	Low
10–20	Moderate
20–30	High
30–40	Very high

Table 2 shows how different temperature ranges influence the rate of mold growth. Higher temperatures typically result in faster mold growth, highlighting the importance of temperature control in preventing mold development.

Time Exposure

The duration of exposure to high humidity and temperature conditions is another vital consideration. Mold does not develop instantly; it requires a sustained period of favorable conditions to grow. Thus, understanding the transient behavior of humidity and temperature within building components is essential for accurate risk assessment [33].

Table 3 summarizes the relationship between exposure time to favorable conditions and the risk of mold growth. Longer exposure times increase the risk, underscoring the need for timely moisture control interventions.

Table 3. Time exposure and mold risk

Exposure time (days)	Mold risk level
<7	Low
7–14	Moderate
>14	High

Combined Effects

In real-world scenarios, these processes do not act in isolation but interact with each other, leading to complex heat and moisture dynamics within building envelopes. For example, solar radiation can increase the surface temperature of a wall, enhancing conduction and potentially

driving moisture diffusion and convection [34]. Understanding these interactions is crucial for accurately predicting the moisture performance of building materials and preventing mold growth (Fig. 1) [35].

Practical Implications

Understanding these fundamental processes allows for the development of effective strategies to manage heat and moisture within buildings. Key strategies include:

- Material Selection: Choosing materials with appropriate thermal and hygric properties to control heat and moisture transfer [36, 37].
- Design Considerations: Incorporating features like vapor barriers, insulation, and ventilation to manage moisture and heat flow [38, 39].
- Climate Adaptation: Tailoring building designs to specific climatic conditions to mitigate the effects of local environmental factors [40].

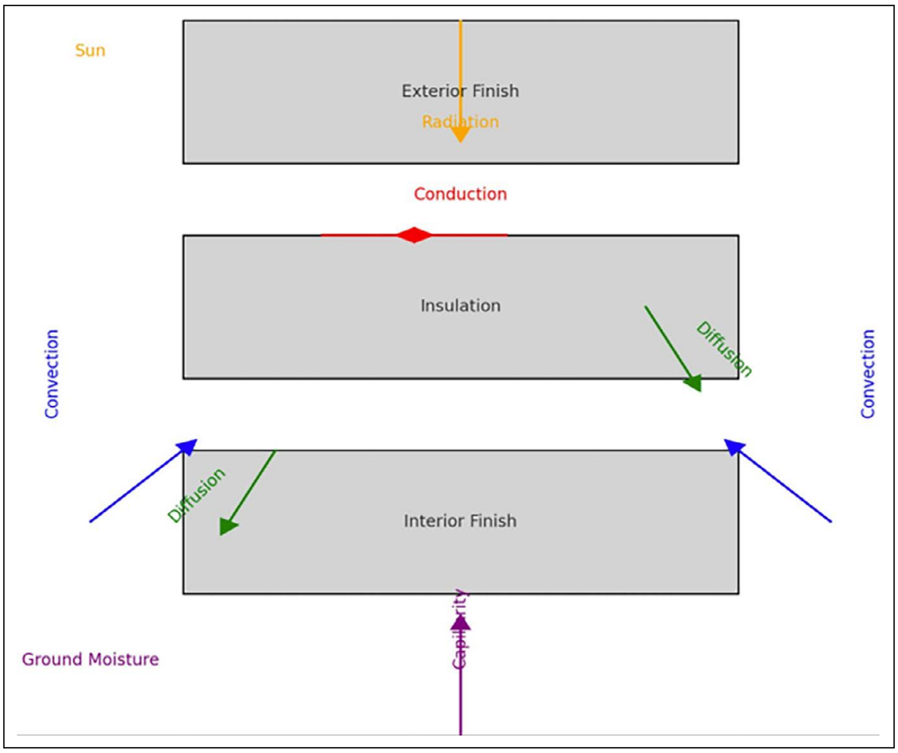

Figure 1. Schematic of heat and moisture transfer processes.

By leveraging the principles of heat and moisture transfer, building designers and engineers can create more resilient and durable structures that minimize the risk of mold growth and ensure occupant comfort and health.

Hydro-Thermal Simulation

To analyze the interactions between heat and moisture and predict mold risk, the study utilizes hygrothermal simulation tools such as WUFI (Wärme und Feuchte Instationär). WUFI simulates the transient behavior of heat and moisture in building components, allowing for the assessment of mold growth risk under varying climatic conditions [41].

Modeling Approaches

1. Steady-State Models: These models assume constant environmental conditions and are useful for understanding basic moisture transport mechanisms. However, they are less effective for predicting mold growth under dynamic conditions.
2. Transient Models: These models consider the time-varying nature of environmental conditions and provide a more accurate prediction of moisture and temperature behavior in building components [42].

Previous Studies

Previous research has highlighted the significance of accurately predicting the moisture behavior in buildings to prevent mold growth. For instance, Sedlbauer (2001) developed models to predict mold formation on building surfaces, emphasizing the need for precise data on humidity and temperature. Similarly, Wang and Brennan (2004) demonstrated the importance of understanding the moisture performance of building envelopes to develop effective mold prevention strategies [43].

MATERIALS AND METHODS

Data Collection

Climate Data involves gathering temperature and humidity data from reliable sources such as meteorological databases or climate models. The data should cover various climatic regions to account for different environmental conditions. Material Properties: Gathering information on the thermal and hygric (moisture-related) properties of materials used in building construction. This includes parameters such as thermal conductivity, specific heat capacity, water absorption coefficient, and vapor permeability.

Model Setup

Wall Assembly Definition: This step involves creating a digital model of the exterior wall in WUFI. The wall assembly includes layers of materials such as exterior cladding, insulation, vapor barriers, and interior finishes.

Inputting Material Properties: Inputting the gathered material properties into WUFI to accurately simulate how each material responds to heat and moisture.

Simulation Execution

Running Simulations: Simulations are run for each climate scenario. This involves setting boundary conditions that reflect the exterior and interior climate conditions, such as temperature, relative humidity, and solar radiation.

Duration: Simulations are often run over extended periods (e.g., one year) to capture seasonal variations and long-term trends in temperature and humidity within the wall assembly.

Analysis

Evaluating Results: Post-processing the simulation data to evaluate how temperature and humidity levels change over time within the wall assembly. This helps identify periods and conditions where the risk of mold growth is highest.

Mold Growth Risk: Assessing the risk of mold growth based on criteria such as the duration of high humidity levels and temperature ranges conducive to mold development.

Sımulation Steps

Climate Data

Profiles: Utilizing temperature and humidity profiles for different climatic regions, such as hot and humid, cold and dry, or temperate climates. This ensures that the simulations are representative of various environmental conditions.

Building Materials

Properties: Inputting detailed properties of commonly used building materials like wood, concrete, brick, and insulation materials. Accurate data ensures reliable simulation results.

Design Elements

Wall Assembly Configuration: Configuring the details of the wall assembly, including the sequence of materials, thickness of layers, and presence of vapor barriers or insulation.

Insulation Types: Testing different insulation types (e.g., fiberglass, foam, mineral wool) to see how they impact moisture and temperature behavior.

Results

Transient Behavior of Humidity and Temperature,

Simulation Data: The results show how humidity and temperature levels within the wall assembly change over time, illustrating the dynamic response to external and internal climate conditions.

Critical Periods: Identifying specific times of the year when the conditions are most favorable for mold growth, such as prolonged periods of high humidity.

Figures and Tables

Figures 2-4 show relative humidity levels within the wall over time for different climate scenarios. This helps visualize how different climates affect moisture levels in the wall assembly.

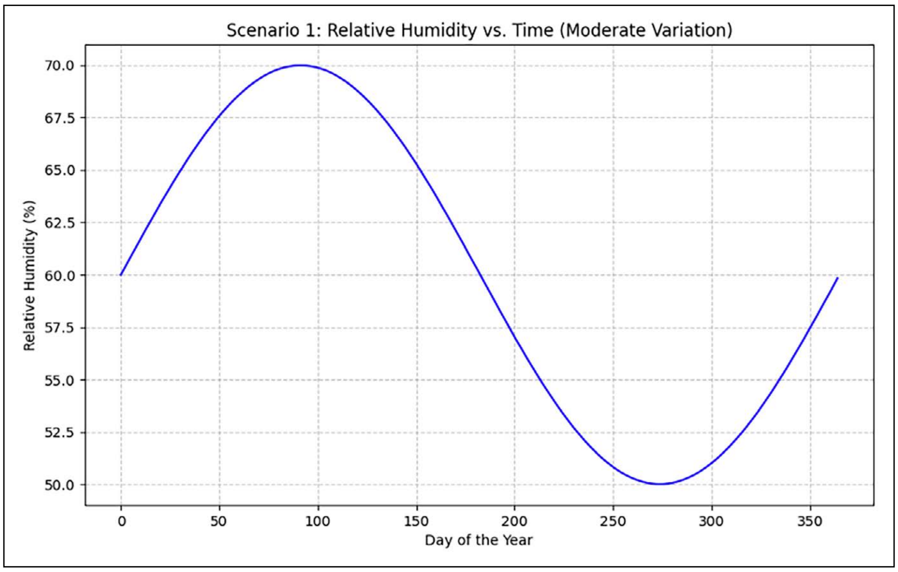

Figure 2. Moderate humidity variation.

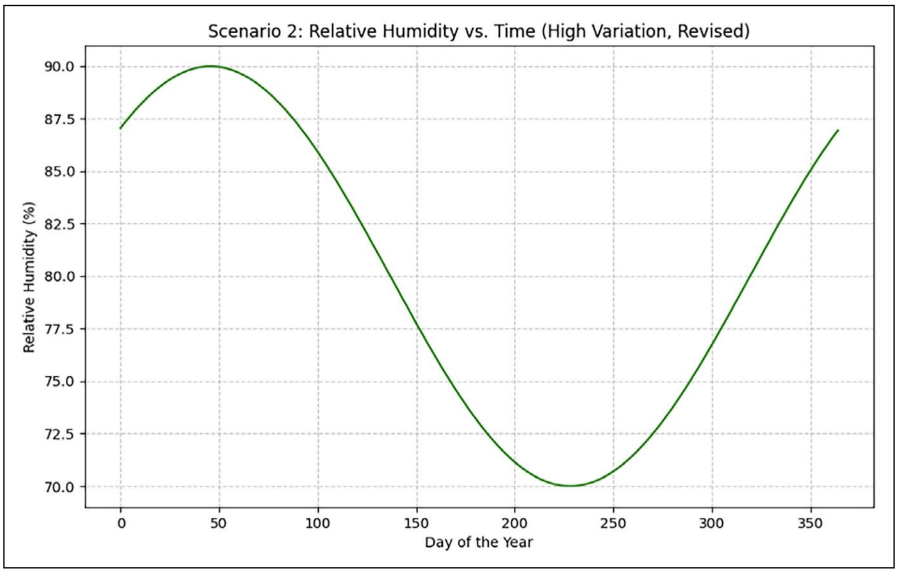

Figure 3. High humidity variation.

Table 4 Summarizes the mold growth risk for various building materials under different climate scenarios. It provides a clear comparison of how each material performs in terms of mold resistance.

Scenario 1: Moderate Humidity Variation

- Description: This scenario shows a moderate variation in humidity levels, fluctuating around an average of 60%.
- Amplitude: The humidity varies by about 10%, ranging from 50% to 70%.
- Seasonal Peaks: Peaks in the middle of the year, indicating a higher risk of mold growth during this period.

Scenario 2: High Humidity Variation

- Description: Represents a climate with significant humidity variation, with an average around 50%.
- Amplitude: The humidity varies by about 15%, ranging from 70% to 90%.
- Phase Shift: The peaks are shifted compared to Scenario 1, showing different seasonal timings.
- Risk Implications: Higher risk for mold growth, requiring advanced moisture control measures.

Scenario 3: Low Humidity Variation

- Description: Shows stable humidity levels throughout the year, with an average of 55%.
- Amplitude: Small variation of about 5%, ranging from 50% to 60%.
- Risk Implications: Lower risk for mold growth, with stable conditions posingminimal threat.

These figures help visualize how different climate scenarios affect moisture levels within the wall assembly, aiding in the assessment of mold growth risk.

To provide a full analysis, it is necessary to define the materials used in each scenario. Materials are often chosen based

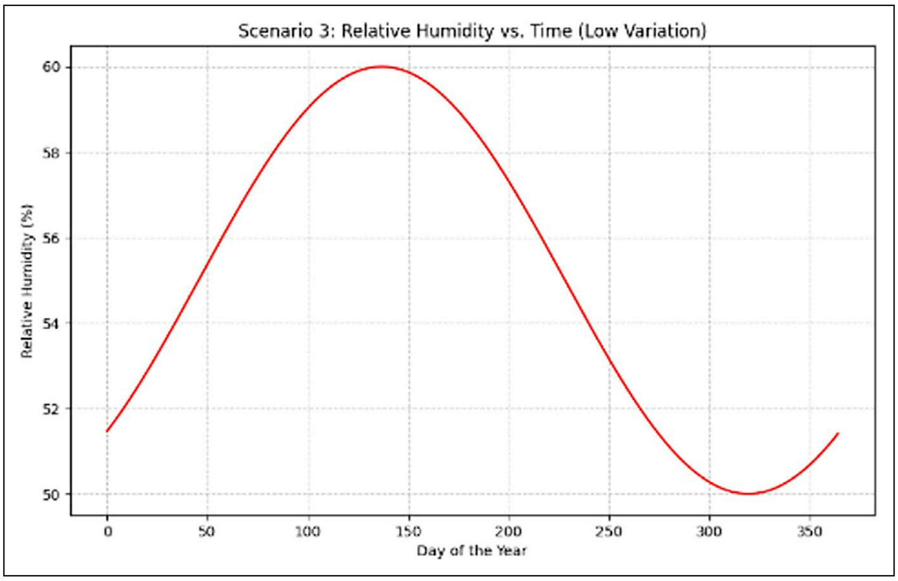

Figure 4. Low humidity variation.

Table 4. Various building materials under different climate scenarios

Material	Climate scenario	Mold risk level
Material A	Scenario 1	High
Material B	Scenario 2	Medium
Material C	Scenario 3	Low

on traditional building procedures and their capacity to resist various climate conditions.

Scenario 1: Moderate Humidity Variation

- Exterior Cladding: Brick veneer
- Insulation: Fiberglass batt insulation
- Sheathing: Oriented strand board (OSB)
- Vapor Barrier: Polyethylene sheet
- Interior Finish: Gypsum drywall

Characteristics:

- Brick Veneer: Durable and provides moderate thermal mass.
- Fiberglass Insulation: Commonly used, provides good thermal resistance but can be susceptible to moisture.
- OSB Sheathing: Standard sheathing material, has moderate moisture resistance.
- Polyethylene Vapor Barrier: Prevents moisture from penetrating the wall cavity.
- Gypsum Drywall: Standard interior finish, can be affected by high humidity.

Scenario 2: High Humidity Variation,

- Exterior Cladding: Stucco
- Insulation: Spray foam insulation
- Sheathing: Plywood
- Vapor Barrier: Smart vapor retarder (e.g., MemBrain)
- Interior Finish: Moisture-resistant gypsum board (green board)

Characteristics:

- Stucco: Breathable material that can handle high humidity but requires maintenance.
- Spray Foam Insulation: Provides excellent thermal resistance and acts as an air barrier.
- Plywood Sheathing: Higher moisture resistance compared to OSB.
- Smart Vapor Retarder: Adjusts permeability based on humidity levels, providing better moisture control.
- Moisture-Resistant Gypsum Board: Better suited for high humidity environments.

Scenario 3: Low Humidity Variation

- Exterior Cladding: Vinyl siding
- Insulation: Rigid foam insulation (e.g., extruded polystyrene)
- Sheathing: Fiberboard
- Vapor Barrier: Kraft-faced insulation (integrated vapor retarder)
- Interior Finish: Standard gypsum drywall

Characteristics:

- Vinyl Siding: Low maintenance and good moisture resistance.
- Rigid Foam Insulation: Provides good thermal resistance and moisture barrier properties.
- Fiberboard Sheathing: Lightweight and has moderate moisture resistance.
- Kraft-Faced Insulation: Provides some vapor resistance, suitable for low humidity variations.
- Standard Gypsum Drywall: Commonly used, suitable for environments with low humidity fluctuations.

Table 5. The mold growth risk for various building materials under different climate

Material	Climate scenario 1	Climate scenario 2	Climate scenario 3
Exterior cladding			
Brick veneer	Low	Medium	Low
Stucco	Medium	High	Medium
Vinyl siding	Low	Low	Low
Insulation			
Fiberglass batt ınsulation	Medium	High	Medium
Spray foam insulation	Low	Low	Low
Rigid foam insulation	Low	Low	Low
Sheathing			
OSB	Medium	High	Medium
Plywood	Medium	Medium	Low
Fiberboard	Medium	High	Medium
Vapor barrier			
Polyethylene sheet	Low	Medium	Low
Smart vapor retarder	Low	Low	Low
Kraft-faced ınsulation	Medium	Medium	Low
Interior finish			
Standard gypsum drywall	Medium	High	Medium
Moisture-resistant gypsum board (green board)	Low	Medium	Low

**: Indicates insulation materials, which play a key role in regulating both thermal and moisture behavior of the wall assemblies.

Comparative Analysis of Materials

- Scenario 1 materials are chosen for moderate conditions, balancing cost and performance with a standard moisture management approach.
- Scenario 2 materials are selected to handle significant humidity variations, emphasizing high moisture resistance and advanced vapor control to mitigate mold risk.
- Scenario 3 materials are optimized for stable conditions, focusing on simplicity and cost-effectiveness with basic moisture control.
- By selecting appropriate materials based on the expected climate conditions, the study aims to minimize the risk of mold growth and enhance the durability and safety of building envelopes.

Table 5 is a detailed table summarizing the mold growth risk for various building materials under different climate scenarios.

Explanation of Risk Levels:

- Low: The material is unlikely to support mold growth under typical conditions for this scenario.
- Medium: There is a moderate risk of mold growth, requiring some moisture control measures.
- High: The material is highly susceptible to mold growth under these conditions, necessitating robust moisture control strategies.

Key Observations:

- Scenario 1 (Moderate Humidity Variation): Most materials have a medium risk due to moderate fluctuations in humidity. Standard materials like OSB and fiberglass insulation show higher risk compared to more resistant materials like rigid foam insulation.
- Scenario 2 (High Humidity Variation): This scenario presents the highest mold growth risk. Materials such as OSB, fiberglass insulation, and standard gypsum drywall are particularly vulnerable, requiring advanced moisture control and careful material selection.
- Scenario 3 (Low Humidity Variation): The stable humidity levels result in generally low mold growth risk for most materials. Even standard materials perform well, with minimal need for specialized moisture management.
- Assessing mold growth risk in various materials under different climates helps designers and builders enhance building durability and safety.

RESULTS AND DISCUSSIONS

Simulation Setup

The hydro-thermal simulations were conducted on a standard exterior wall assembly using WUFI software. Key parameters included:

- Climate Data: Temperature and humidity profiles from hot and humid, cold and dry, and temperate climates.

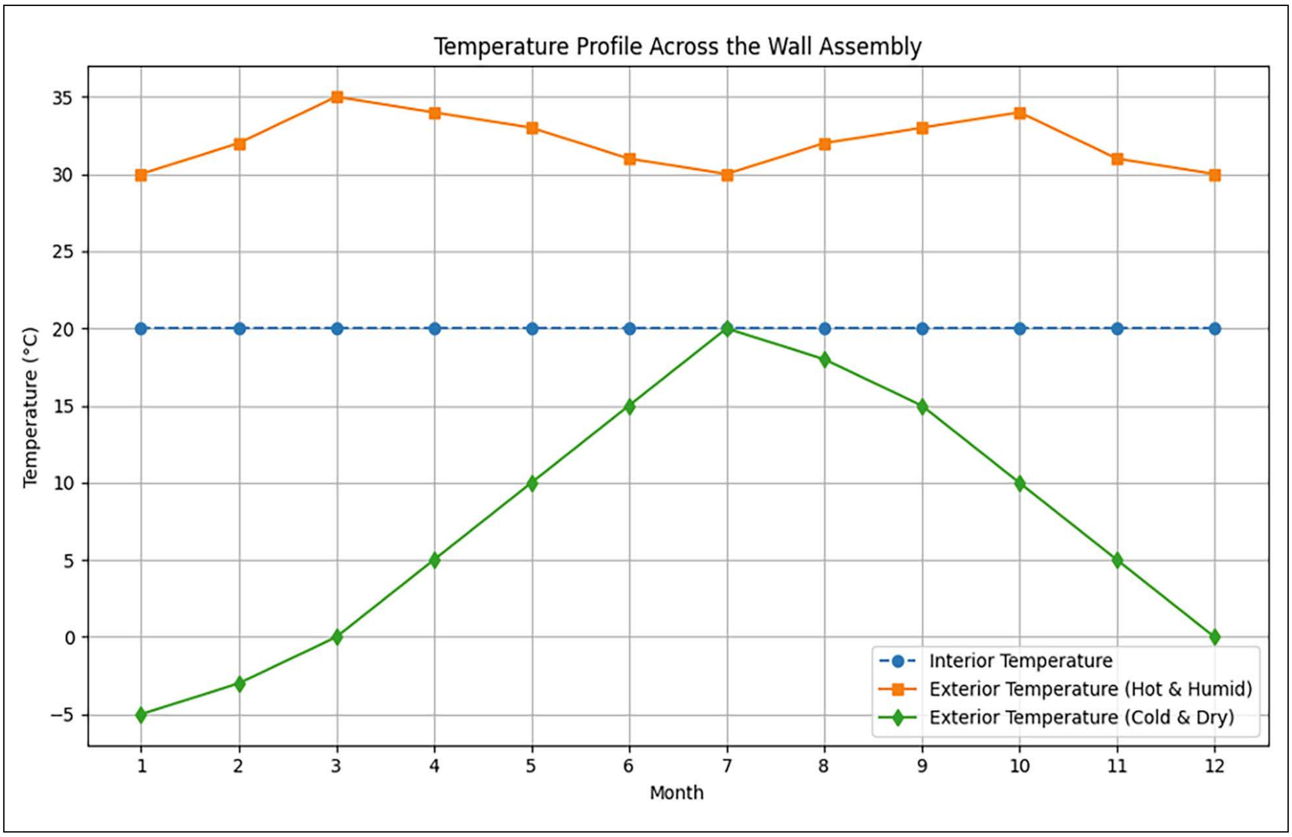

Figure 5. Temperature profile.

- Material Properties: Thermal conductivity, specific heat capacity, vapor permeability, and moisture absorption characteristics.
- Boundary Conditions: Indoor conditions maintained at 20°C and 50% relative humidity (RH), with outdoor conditions varying based on the climate data.

Temperature And Humidity Profiles

The temperature profile across the wall assembly showed significant variation between the interior and exterior surfaces (Fig. 5). In hot and humid climates, the exterior surface temperature reached up to 35°C during peak summer months, while the interior temperature remained stable around 20°C, demonstrating the insulation's effectiveness in maintaining indoor comfort.

The relative humidity profile indicated higher humidity levels at the exterior surface in humidclimates, often exceeding 80% during peak humidity periods. The insulation layer showed moderate humidity levels, while the interior surface maintained a constant 50% RH, highlighting the importance of vapor barriers in controlling moisture ingress.

Moisture Content and Mold Growth Risk

The moisture content analysis revealed that the exterior cladding, particularly in humid climates, experienced the highest moisture content, posing a significant mold growth risk. The insulation layer, although showing moderate moisture levels, still presented a moderate risk, emphasizing the need for effective moisture management strategies (Table 6).

Seasonal Variations

The simulation results highlighted seasonal variations in temperature and humidity, which directly influenced the mold growth risk. For example, during the summer months, higher temperatures and humidity levels at the exterior surface increased the mold growth risk. In contrast, winter conditions with lower temperatures and humidity levels reduced the risk but did not eliminate it entirely.

Impact of Material Properties

The choice of materials significantly impacted the hydro-thermal performance of the wall assembly. Materials with high thermal conductivity, such as metal cladding, showed greater temperature fluctuations and higher moisture content, increasing the mold growth risk. Conversely, materials with low thermal conductivity and high vapor permeability, such as mineral wool insulation, demonstrated better moisture management and lower mold growth risk.

Table 6. Moisture content and mold growth risk

Material layer	Moisture content (%)	Mold growth risk
Exterior cladding	12%	High
Insulation	8%	Moderate
Vapor barrier	2%	Low
Interior finish	3%	Low

Table 7. Recommended design strategies based on simulation results

Strategy	Effectiveness	Recommendation
Use of vapor barriers	High	Essential for all climate conditions
High-performance ınsulation	High	Critical in humid and cold climates
Adequate ventilation	Moderate to high	Important in all climate conditions
Reflective exterior surfaces	Moderate to high	Recommended in hot climates

Effectiveness Of Design Strategies

The simulation results validated the effectiveness of various design strategies in mitigating mold growth risks (Table 7):

- Vapor Barriers: Proper placement and selection of vapor barriers significantly reduced moisture ingress and condensation within the wall assembly.
- Insulation: High-performance insulation materials effectively maintained stable indoor temperatures and reduced humidity levels, lowering mold growth risk.
- Ventilation: Adequate ventilation in wall cavities and indoor spaces helped control humidity levels, further reducing the risk of mold development.

Practical Implications

The findings underscore the importance of considering climate-specific conditions during the design phase to ensure the longevity and safety of building materials. By leveraging hydro-thermal simulations, designers can make informed decisions about material selection, insulation, and moisture control strategies, ultimately enhancing building performance and occupant comfort.

CONCLUSION

The study demonstrates that hydro-thermal simulations are highly effective in assessing mold development risks in building envelopes. By understanding the transient behavior of humidity and temperature, designers can make informed decisions to minimize mold growth risks. The findings emphasize the importance of considering climate-specific conditions during the design phase to ensure the longevity and safety of building materials. Hydro-thermal simulations are crucial in modern building science, providing deep insights into the interactions between heat and moisture within building envelopes. By accurately modeling these interactions, hydro-thermal simulations support the development of resilient, energy-efficient, and healthy buildings. Understanding the results of these simulations enables designers to optimize materials and construction techniques, ultimately leading to cost savings, improved performance, and enhanced occupant comfort.

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. USE OF AI FOR WRITING ASSISTANCE Not declared.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

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