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Article Title:

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DOI:

https://doi.org/10.14324/ucloepreprints.305.v1

Preprint Statement:

This article is a preprint and has not been peer-reviewed. The article has been submitted to UCL Open Environment (ISSN: 2632-0886) and is under consideration for publication following peer review.

Preprint Version:

This is version of this article.

Data Availability Statement:

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Keywords:

indoor envrionment quality, timber framed wall, CFCS, clay masonry veneer, indoor mould growth risks, Hygrothermal performance, intermittent conditioning, uncontrolled relative humidity, energy-efficient house

Relative Humidity in Intermittently Conditioned Energy-Efficient Homes: A Preliminary Hygrothermal Assessment of Indoor Condensation and Mould Risk

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Abstract

Rising global temperatures and increasing energy demand have led to more stringent energy-efficiency requirements in buildings. While these measures reduce energy use, they may unintentionally increase the risk of indoor and interstitial moisture accumulation and mould growth. Highly insulated and airtight dwellings, combined with occupant-controlled ventilation and intermittent space conditioning without relative humidity (RH) regulation, can create environments conducive to mould, threatening indoor air quality, occupant health, and building durability. In Australia, the 2022 National Construction Code mandates a minimum 7-Star building envelope focused energy rating for new residential dwellings. Unlike international standards, Australian regulations include intermittent conditioning without specifying indoor RH limits, potentially increasing moisture-related risks. This study examines the effects of intermittently conditioned indoor climate on interstitial moisture accumulation and mould growth in two of the most common low-rise timber-framed wall systems; clay masonry veneer and compressed fibre-cement sheet cladding within temperate Australian climate zones. Ten-year transient hygrothermal simulations were conducted to quantify moisture and mould risks. Results show, without RH control, indoor conditions frequently exceed the internationally recommended 70% RH threshold, significantly increasing interstitial mould risk, particularly in bedrooms and open-plan living space. Comparisons with continuous conditioning, per ASHRAE 160, indicate lower risks under continuous conditions. Mitigation strategies, including ventilated cavities and internal vapour control layer, were effective under continuous conditioning but exhibited inconsistent performance under conditions of unregulated RH in intermittent conditioning. The findings reveal the limitations of continuous conditioning assumptions for moisture control design and underscore the problem of underestimating moisture risks in buildings.

Keywords: energy-efficient house; uncontrolled relative humidity; intermittent conditioning; hygrothermal performance; indoor mould growth risk; clay masonry veneer; CFCS; timber-framed wall; indoor environment quality

1. Introduction

1.1 Background

As response to global climate change and energy crisis, energy-efficient building design is one of the central strategies for achieving carbon-neutral goals, with a growing emphasis on airtightness and weather-resilient construction (1–4). This shift is also reflected in the Australia National Construction Code (NCC) 2022, which mandates a minimum 7-Star building envelope focused energy rating for new residential buildings. Notably research has found that, while reducing energy losses from indoor heating and cooling, this approach can also lead to unintended consequences. Particularly by increasing the risk of indoor and interstitial condensation and mould growth, affecting indoor environmental and air quality (5–8). Indoor air quality (IAQ), a key determinant of occupant health and comfort, is closely linked to indoor relative humidity (RH) (9–11). Elevated RH levels create favourable conditions for microbial proliferation, most notably mould, which undermines both occupant health and building durability (12–14). Interstitial mould or fungal growth within concealed assemblies, such as wall cavities, further threatens structural integrity and often remains undetected until significant damage occurs. The World Health Organization (WHO) recognises dampness and mould as critical contributors to respiratory illness and allergies, underscoring their public health significance (15). Research demonstrates that mould germination can occur at RH levels above 70% [8–10], whereas maintaining indoor RH below 60% is generally advised to minimise the risk of growth.

1.2 The intermittently conditioning

The challenge of balancing energy efficiency and moisture control is particularly pronounced in the Australian context. Unlike standards in many northern hemisphere countries, such as United States, Japan, North China and much of Europe (including Germany, the United Kingdom, and the Netherlands), where continuous indoor conditioning is common, Australian regulations require intermittent conditioning of habitable rooms without specifying numerical requirements for indoor RH. From a building physics perspective, while this intermittent conditioning strategy reduces energy consumption (16), it can affect moisture-related risks, particularly in airtight, highly insulated dwellings with occupant-controlled ventilation (8,17–19). Additional factors, such as thermal bridging, ventilation practices and inappropriate insulation could further exacerbate these vulnerabilities (20–22).

Internationally, a range of methods has been employed to investigate building environmental RH and mould risk, including predictive modelling validated by laboratory testing (23,24), field-based sampling to detect hidden mould (25,26), and computer-based hygrothermal simulations of moisture transport and accumulation in building envelopes (27–29). Among these methods, transient hygrothermal simulations are particularly effective to provide a time-efficient and reliable approach to approximating the long-term impacts of RH variation under representative operating conditions.

By examining the interplay between intermittent conditioning, RH management, and mould proliferation, this research yields insights that are highly applicable to Australia as well as other countries that are moving away from continuous conditioning towards intermittent building conditioning. Notably, at COP28 in 2023, representatives from more than 63 countries, including the United States, Canada, and leading members of the European Union, committed to reducing emissions associated with cooling by shifting away from continuous, energy-intensive cooling systems through the adoption of passive cooling strategies and enhanced efficiency standards (30–32). In response, building codes in several regions actively encourage intermittent conditioning, alongside the implementation of minimum energy performance requirements for active systems.

1.3 The goal of this study

The goal of this study is to investigate how different conditioning operations influence indoor environmental quality. Specifically, it aims to compare continuous conditioning with both temperature and RH control against intermittent conditioning with no control of RH, and to assess how these approaches affect interstitial condensation and mould growth risks across studied climates.

To achieve this, WUFI transient hygrothermal and bio-hygrothermal simulations are applied to examine the impact of uncontrolled indoor RH in two of Australia's most common low-rise wall systems: timber-framed clay masonry veneer and compressed fibre cement sheet (CFCS) cladding.

Building on the Australian and international context of intermittent conditioning, the study focuses on three temperate climate zones (CZ), NatHERS climate zone CZ 21 represents medium density urban environment, CZ 64 is a cool temperate coastal zone, and CZ 66 is inland with the highest relative humidity of the three, as detailed later in this paper. To evaluate the external wall performance. Two indoor conditioning scenarios are compared: (1) continuous control of indoor temperature and RH in accordance with ASHRAE 160 and AIRAH DA07 thresholds, as studied in previous research (33,34), and (2) controlled indoor temperature with uncontrolled RH in intermittent conditioning, which is the focus of this study. Furthermore, mitigation strategies, including ventilated cavities and interior vapour control layer combinations are also assessed.

1. Settings and climate zones

2.1 Settings

To more accurately reflect an uncontrolled RH within an intermittent air-conditioning scenario of an Australian energy-efficient home, the research conducted a building energy rating simulation using AccuRate. AccuRate is a simulation tool developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) for the Australian Nationwide House Energy Rating Scheme (NatHERS). AccuRate is used to calculate the indoor environmental conditions of a typical 7-Star rated detached house in south-eastern Australia. The floor plan, shown in **Figure 1**, is a four-bedroom home with an interior volume of 366m^3 and a floor area of 152.5 m^2. This plan represents a typical low-rise timber-framed house design in southeastern Australia, consistent with previous research (33,35) .

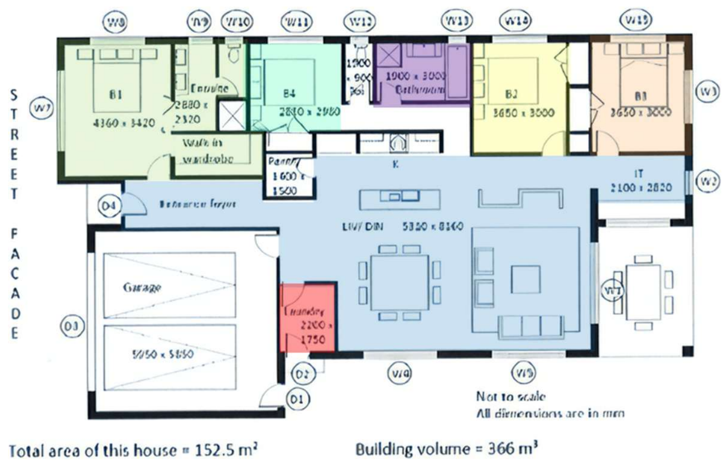


Figure 1: The diagram of the floor plan of assessed house (Not to scale).

The timber-framed clay masonry veneer (or brick veneer)and compressed fibre cement sheet (CFCS) clad external wall systems, represent 54.2% and 20.3% of new dwellings by 2024 (36), this study examines the climatic regions experiencing the highest rates of residential development, see Table 1. Their widespread adoption makes them critical to understanding the moisture performance of typical Australian building envelopes under the updated energy efficiency requirement and local conditioning practice (36,37). The primary focus is on analysing moisture behaviour and interstitial mould growth risk associated with these selected external wall systems. And further test the effectiveness of mitigations that are current suggested by Australian Building Codes Board, and Design Professionals (Architects, Engineers, Building Designers, Building Physicists).

Table 1. NatHERS climate zones selected for this study.

NatHERS climate	NCC climate	Location of weather station	Percentage of New Houses Built by 2024
21	6	Melbourne	6%
22	6	East Sale	12%
27	4 and 6	Mildura	9%
60	6	Tullamarine	12%
61	4 and 6	Mt Gambier	2%
63	6	Warrnambool	4%
64 (+62)	6	Cape Otway (+Moorabbin)	25%
66	4 and 6	Ballarat	30%

2.2 Two Australian climate zones: NCC & NatHERS

In studies of energy-efficient housing design and assessment in Australia, two primary climate classification systems are commonly used. The NCC climate zones divide Australia into eight broad regions, to guide regulatory requirements for building design, construction practices and material choices (38). In contrast, the NatHERS framework defines 69 more detailed climate zones allocated by postcode (39), which are applied specifically in thermal performance modelling of residential buildings. While both systems seek to capture climatic variability, the NCC zones are primarily used for compliance with construction regulations, whereas the NatHERS zones provide finer-grained resolution for building energy rating assessments. This study references NCC climate zones to align with regulatory requirements in modelling but also incorporates the climatic diversity, particularly the variation in relative humidity and temperature, captured by NatHERS zones to ensure a more robust evaluation of building performance. The two climate zone maps are shown in Figure 2 (39). The red dashed line highlights the locations of this research.

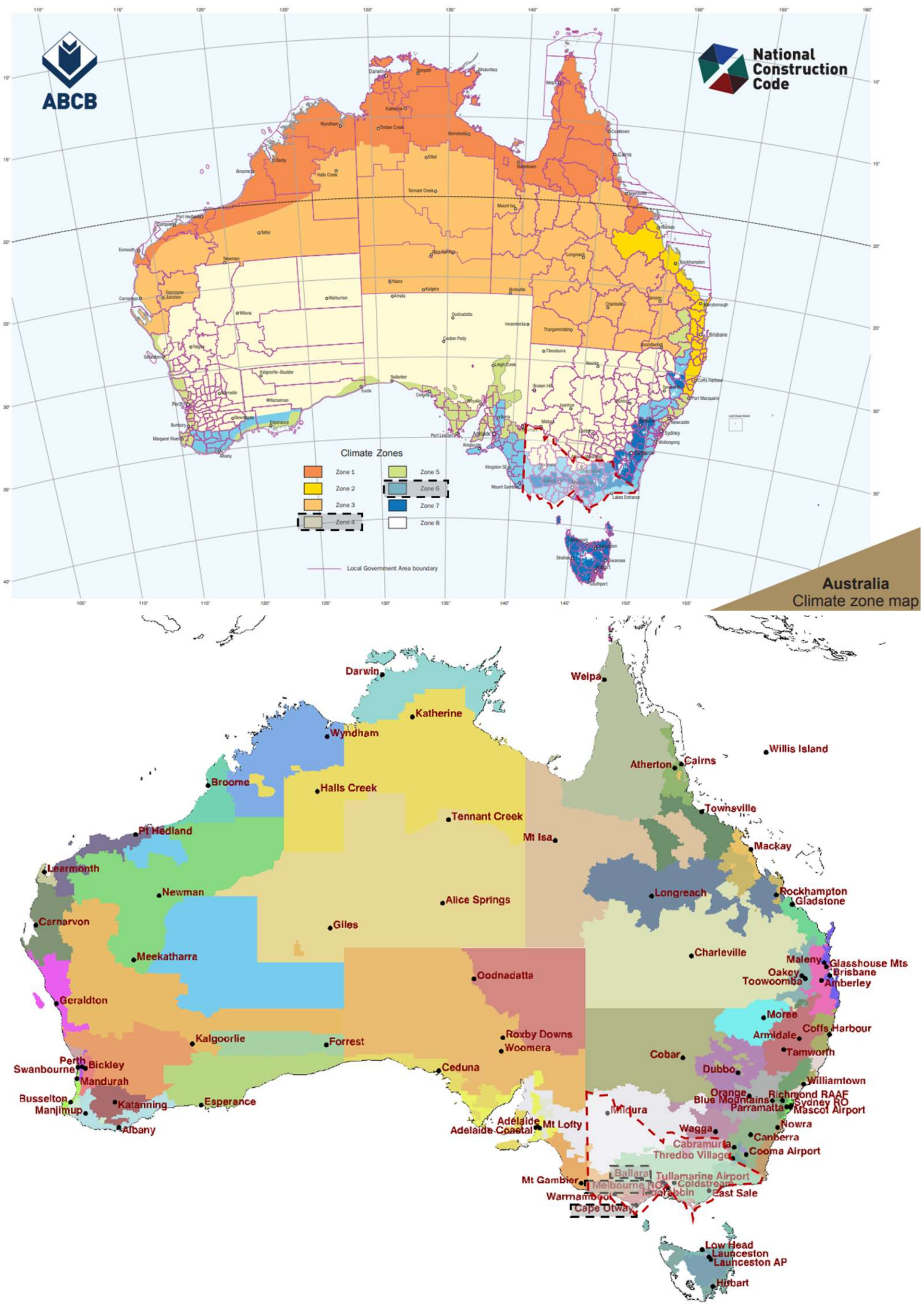


Figure 2: NCC climate zone (top), NatHERS climate zone (bottom).

2.3 Assessed climate zones

To better understand the climatic context that underpins the hygrothermal assessment, see Figure 3. This figure illustrates the monthly climate characteristics, specifically RH and average temperature for three distinct climate zones: CZ 21, CZ 64, and CZ 66. The graphs illustrate the monthly RH of 1.5 interquartile range (IQR) and average temperature for each climate zone. They provide crucial insights into annual climatic fluctuations, which are essential for predicting a building's hygrothermal performance.

2.3.1 Relative Humidity (RH)

The box plots show the monthly maximum, medium, and minimum RH (in %).

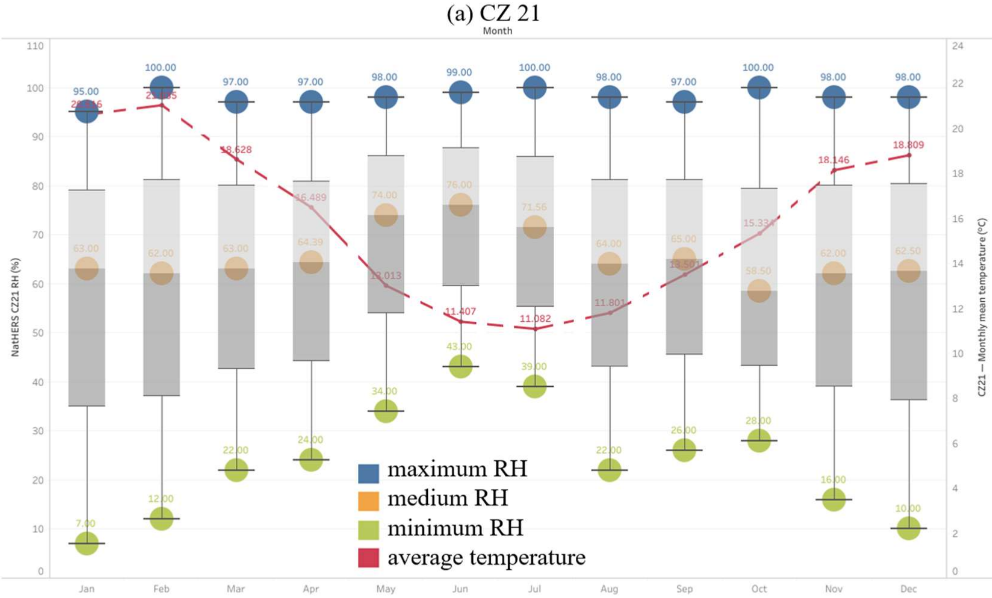
- All three zones exhibit a consistently high maximum RH, frequently reaching 100% throughout the year. This suggests that the air is often saturated or near saturation, which is a key indicator for potential condensation and mould growth risks on surfaces or within building envelope layers, particularly during cooler periods.
- The median RH (orange dots in grey bar) generally remains high, hovering around 60% to 80%, indicating a predominantly humid climate.
- The spread between maximum and minimum RH is significant, with minimums (green dots) occasionally dropping below 20% in some months (e.g., CZ 66 in May and June), suggesting periods of relatively dry air that could affect the drying potential of materials.

2.3.2 Monthly Average Temperature

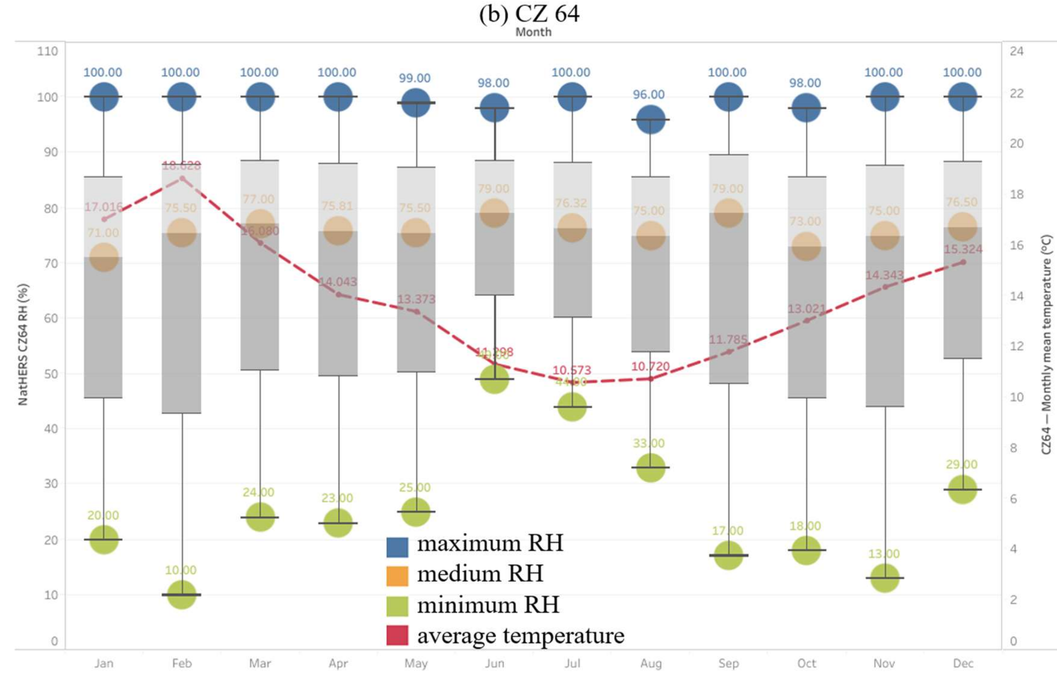
The red dashed line represents the monthly average temperature (in ∘C).

- All zones follow a typical annual cycle, peaking in the summer months (January/February) and reaching their minimums in winter (June to August).
- CZ 21 shows the highest average temperatures, peaking above 20∘C and only dropping slightly below 10∘C in winter.
- CZ 64 and CZ 66 display lower overall average temperatures. Particularly CZ 66, which has a minimum average temperature of around 6∘C to 8∘C in mid-winter. The lower winter temperatures, combined with the persistently high RH, significantly increase the risk of interstitial and surface condensation, as the temperature of building elements are more likely to drop below the dew point.

(a) CZ 21



(b) CZ 64



(c) CZ 66

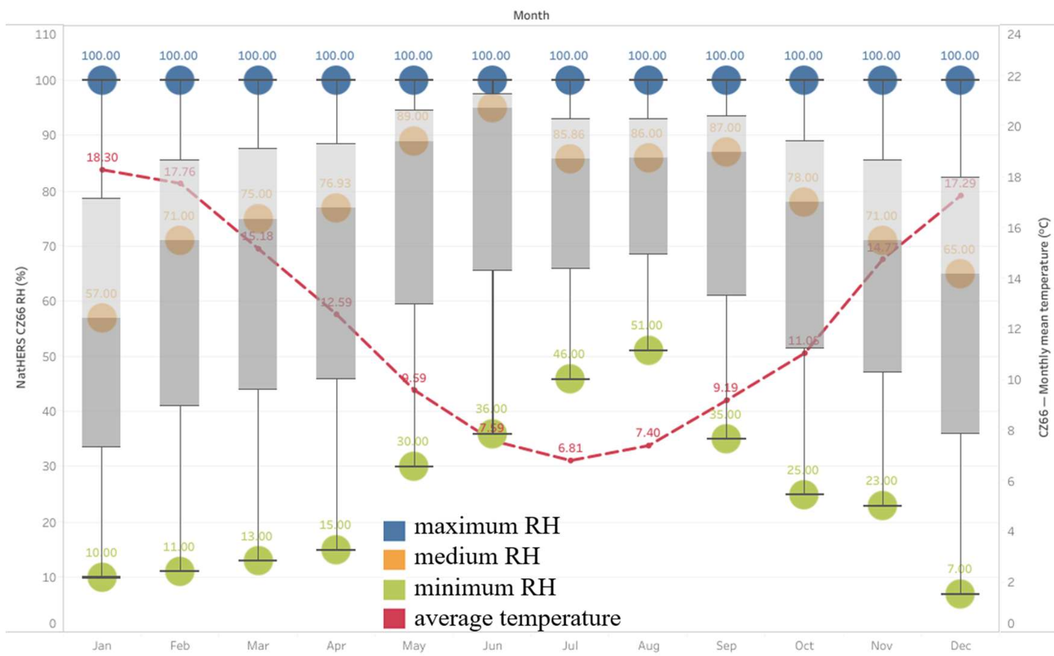


Figure 3: Monthly climate characteristics of NatHERS CZ 21, CZ 64 and CZ 66.

2.3.3 Hygrothermal and bio-hygrothermal Assessment

The data in Figure 3 is fundamental to the hygrothermal assessment, as it defines the environmental loads that the building envelope must withstand.

- Moisture Management: The persistently high RH requires a building design that prioritizes vapour and moisture control. Materials and assemblies must be selected for their ability to withstand high moisture content without degradation (e.g., rot, corrosion) and to allow for adequate drying capacity to manage trapped moisture.

- Condensation Risk: The combination of low winter temperatures and high RH (especially the 100% maximums) highlights the critical need to assess the risk of both surface condensation (mould risk) and interstitial moisture (material damage, insulation failure). A detailed WUFI or similar simulation, informed by this data, is necessary to determine the required thermal resistance and vapour control layer placement for safe envelope design.

- Energy Consumption: The temperature variation dictates the heating and cooling demand. The mild winters in CZ 21 suggest a lower heating load compared to CZ 66, but the high humidity across all zones means that latent cooling (dehumidification) may be a significant factor in summer energy use.

- Climate Zone Differentiation: The minor but distinct differences between the zones (e.g., the lower winter temperatures in CZ 66) underscore the necessity of performing a zone-specific hygrothermal analysis rather than applying a single design solution across all areas.

2. Method

3.1 Indoor climate calculation

Indoor climate data are fundamental to evaluating hygrothermal and bio-hygrothermal risks in residential buildings under varying conditioning regimes. Although ASHRAE 160, adopted in Australia as AIRAH DA 07, provides widely accepted criteria, it does not address the uncontrolled RH of intermittent conditioning patterns in Australian homes. In practice, the absence of explicit indoor temperature and relative humidity thresholds allows dwellings to operate beyond recommended comfort levels, particularly with uncontrolled RH under intermittent operation. To capture these localised conditions, this study employed the AccuRate simulation tool within the Nationwide House Energy Rating Scheme (NatHERS), applying an intermittent conditioning schedule consistent the prescribed operating patterns and thermostat settings within the national building regulations (NCC) (see Table 2).

Table 2: Intermittent conditioning schedules, NCC2022, volume2, summary of table H6V2a.

Hour ending at	Duration(H)	Habitable rooms other than bedrooms	Bedrooms
1:00-6:00	6	OFF	ON
7:00-9:00	3	ON	ON
10:00-18:00	9	ON	OFF
19:00-23:00	5	ON	ON
0:00	1	OFF	ON
total:		On 16 hours, 66.7% of a day	On 14hours, 58.3% of a day

AccuRate simulates hourly indoor temperature profiles for each room by incorporating variables such as building layout, wall orientation, room function, construction material and expected occupancy. Interior moisture generation applied the principles of a four-bedroom home, as specified in ASHRAE160,

below.

Table 3: Residential design moisture generation rates form ASHRAE160, 2016.

Number of bedrooms	Number of occupants	Moisture generation rate		
1 bedroom	2	7L/day	0.8×10^{-4}kg/s	0.64b/h
2 bedrooms	3	9L/day	1.0×10^{-4}kg/s	0.83b/h
3 bedrooms	4	10L/day	1.2×10^{-4}kg/s	0.92b/h
4 bedrooms	5	11L/day	1.3×10^{-4}kg/s	1.01b/h
Additional bedrooms	+1 per bedroom	+1L/day	$+0.1 \times 10^{-4}$kg/s	+0.11b/h

This method allows the simulation to capture the dynamic fluctuations of indoor relative humidity under typical Australian living conditions, including moisture generation by occupants. This method enables the simulation to reflect the dynamic fluctuations of indoor relative humidity under typical Australian living conditions, characterised by intermittent air conditioning.

The indoor climate profiles calculated from AccuRate software are used as critical input for WUFI ©Pro 6.0 and WUFI©VTT (32,33), transient simulation tools employed for assessing heat and moisture transport through building envelopes and the prediction of mould growth risk. An uncontrolled RH intermittent conditioning scenario is modelled, based on the profiles derived from AccuRate results, while indoor temperature is maintained within controlled limits (⩽ 21.1 °C), relative humidity can reach up to 100 %.

3.2 Construction requirements of different climate zones

This study selected NatHERS CZ 21, CZ 64 (+CZ 62) and CZ 66 representing three distinct climatic zones within south-eastern Australia. The NCC establishes only three well populated climate zones, whereas NatHERS includes nine finer thermal zones within the areas bounded by this study. The construction material choices for the hygrothermal and bio-hygrothermal simulations in this study were modelled to align with the NCC climate classification requirements. This ensures that the results are directly relevant to the regulatory framework for residential building design and construction in Australia. Accordingly, the base case design incorporates construction details such as compliant external pliable membranes, in line with Standards Australia AS 4200.1: Pliable building membranes and underlays (40,41), as shown in Table 4. In doing so, the study strengthens both the regulatory applicability of its findings and their practical relevance to building performance assessment under realistic moisture exposure conditions.

Table 4. 7-Star Regulatory water vapour diffusion requirements of exterior membranes, NCC 2022.

NCC Climate Zone	Required Exterior membranes	Vapour permeances Min ≥ (µg/N. s)	Vapour permeances Max < (µg/N. s)	Corresponding Water Vapour Diffusion Resistance Factor (These values assume the layer thickness is 1 mm)	Corresponding Water Vapour Diffusion Resistance Factor Applied in this study
CZ 1-3	No requirements				
CZ 4-5	Min Class 3	0.1429	1.1403	≥175.4078 to <1399.5801	1398.0
CZ 6-8	Min Class 4	1.1403	No Max	<175.4078	175.4

In NCC CZ 4, CZ 6 to CZ 8, clay masonry veneer external wall systems are required to incorporate a ventilated and drained cavity between the brickwork and the supporting timber or steel frame. A portion of wind-driven rain typically penetrates the clay masonry veneer and enters this cavity. The cavity, also referred to as an air gap or air space, is typically 40 mm wide, allowing both ventilation and drainage to occur. This arrangement enhances durability by minimising moisture transfer to the structural frame (41), as shown in **Figure 4.**

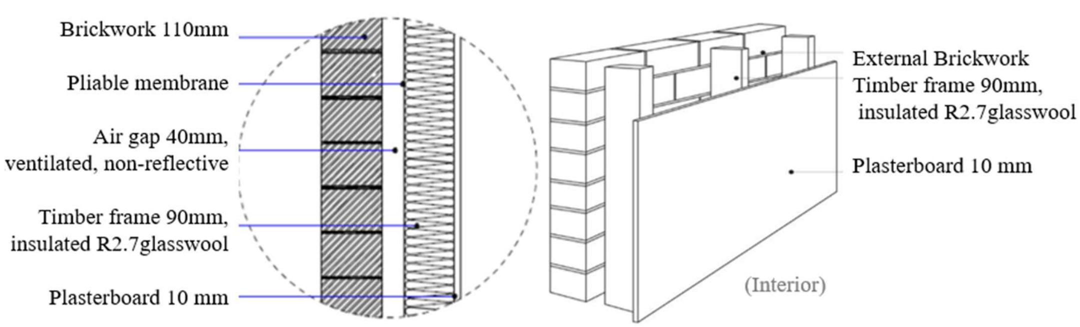


Figure 4. Section and diagram *of clay masonry veneer external wallsystem2003-2025.* (Left: section, right: diagram).

3.3 Parameters of hygrothermal simulation

In this study, strategically positioned monitoring points were used to evaluate how both indoor and outdoor conditions influence the thermal and moisture behaviour of the wall assembly under intermittent conditioning. A default air exchange rate (ACH) of 0.2 was applied, this value aligns with the typical ventilation in recent Australian 7-Star energy-efficient homes (42). Each wall was simulated over a ten-year period to capture thermal performance, moisture content, and changes in water content, highlighting potential condensation and mould growth under uncontrolled relative humidity condition. Material properties for each layer, including vapour permeability, thermal conductivity, and moisture storage, were assigned based on manufacturer data and standard material libraries (see Table 5).

Table 5 Material properties applied in this study.

Material/ construction layer	Layer Thickness (m)	Bulk density (kg/m3)	Porosity (m3/m3)	Spec. Heat Capacity (J/kgK)	Thermal Conductivity (W/mK)	Water Vapour diffusion resistance factor
Fiber Cement Sheathing Board	0.006	1380	0.479	840	0.5	127.7
Extruded Clay Brick	0.11	1820	0.41	959	0.6	9.5
External Membrane	0.001	130	0.001	2300	2.3	175.4
Glass-wool Batted Insulation	0.09	26.2	0.978	1650	0.036	1.8
Interior vapor control layer	0.001	85	0.086	2500	2.4	34000
Paper-faced Gypsum Plaster Board	0.010	880	0.65	1050	0.163	6

Key inputs for the hygrothermal simulations include climatic data, material properties, ventilation rates, and strategically positioned monitoring points within the wall assemblies. To evaluate mitigation strategies, the study examines the use of ventilated cavities and an interior vapour control layer, both individually and in combination, under uncontrolled RH intermittent conditioning patterns. Figure 5 illustrates the comprehensive layering applied to each wall system and the location of cameras are the monitor points from the WUFI Pro software utilised in the research.

Eight monitoring points were systematically placed across four critical layers in each wall assembly to capture bio-hygrothermal performance and moisture dynamics at key material interfaces:

- interior and exterior surfaces of the plasterboard.
- interior and exterior surfaces of the glass-wool batt insulation
- interior and exterior surfaces of the pliable membranes
- interior and exterior surfaces of the cladding

The effect of these strategies on internal moisture buffering and temperature moderation was assessed to determine their suitability for high-performance building envelopes subjected to intermittent, uncontrolled temperature and relative humidity conditions.

Given the significance of moisture-related challenges in timber-framed construction, this study focuses on the point immediately adjacent to the interior surface of the exterior water vapour control layer next to the timber frame and insulation, which has consistently exhibited the greatest risk in previous research (33,34,43).

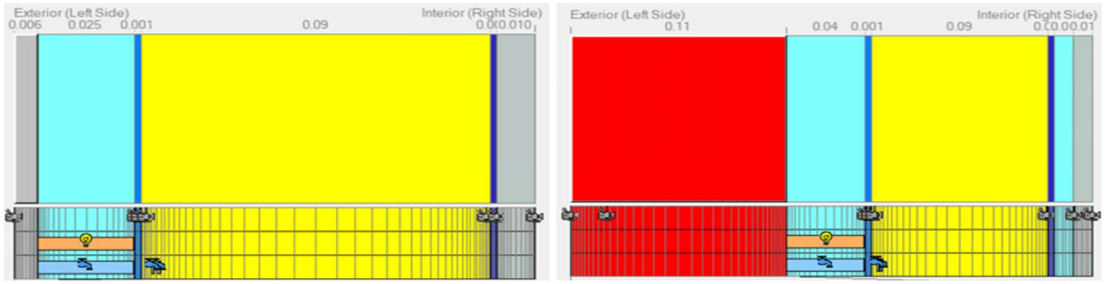


Figure 5: The WUFI monitor point setting with the case applied all layers, CFCS(Left) and Clay masonry veneer (Right)clad external wall systems.

3.4 Bio-hygrothermal mould growth prediction

This study applies bio-hygrothermal simulation to assess the risk of interior surface and interstitial mould growth within building envelopes, using the Mould-growth Index (MI) as a quantitative metric to predict mould proliferation based on environmental and material characteristics. The WUFI VTT add-on software was used to post-process the hygrothermal simulation results to predict mould growth risk (44–46).

The enhancement strategies of lower water vapour diffusion resistivity of the exterior weather resistive layer, the addition of a ventilated cavity and the addition of an interior vapour control layer performance were assessed within the context of the calculate MI. According to NCC 2022 Volume Two (41), the condensation verification approach requires that MI values do not exceed 3.0 at either:

(a) the interior surface of the water control layer, or

(b) any building fabric surface located interior to the water control layer.

The analysis employs the VTT Mould-growth Index model to predict mould formation risk over time on a scale from 0 (no growth) to 3 (visible surface mould covering less than 10 % or microscopic coverage less than 50 %) and 6 (extensive surface colonization, up to 100 % coverage visually). This empirical model incorporates variations in substrate material, surface temperature, and relative humidity to estimate both the accumulation and decline of mould on an hourly basis. The study evaluates mould risk over short-term (seasonal) and long-term (annual) periods, providing a comprehensive assessment of cyclic and sustained hygrothermal exposure on studied wall systems. As this study was focused on the predominance of plantation softwood-based timber framing, the mould sensitivity class of very sensitive was selected.

3. Results

4.1 Indoor climate profiles

The indoor climate is a critical boundary condition for hygrothermal simulation of external wall systems, serving as one of the primary drivers of moisture transport and heat transfer through the building envelope. It also reflects indoor intermittent conditioning pattern. During the heating season, the indoor climate determines the “warm side” moisture load, driving vapour into walls, influencing condensation where dew points occur, and affecting mould growth risk when surface or interface humidity exceeds critical thresholds. Hygrothermal simulations (such as WUFI) model the coupled flow of heat and moisture and therefore require both outdoor and indoor climate data to accurately assess potential risks, including condensation and mould growth.

4.1.1 The RH results of CZ 21

Table 6 below presents the key statistical measures of simulated indoor temperature profiles for different rooms in two plan orientations located within NatHERS CZ 21. For each room, maximum, minimum, and average temperatures are presented alongside the percentage of times when the RH was above 70%, the threshold typically associated with thermal comfort and mould growth risk limits prescribed within ASHRAE 160 and AIRAH DA07.

Overall, indoor RH varied substantially across different functional zones and orientations. In the north-facing plan, the kitchen and living area reached a maximum RH of 95.5%, with RH exceeding 70% for approximately 8.7% of the monitored period, while bedrooms showed RH values above 70% for 13–15% of the time, reflecting higher moisture retention in these zones. Wet areas such as the bathroom and laundry experienced high RH peaks (85.0–86.5%) but shorter periods above 70% (3–4%), indicating lower total moisture loads.

In the east-facing plan, a similar trend was observed, with bedrooms exhibiting sustained periods of RH above 70% (12.7–14.2%), highlighting their susceptibility to elevated moisture loads under intermittent conditioning. Wet zones again showed high peak RH but limited duration above critical thresholds. Notably, the En-suite and toilet zones maintained comparatively lower average RH (47–48%) and short durations above 70%, consistent with lower moisture generation or more effective ventilation. These results indicate that intermittent indoor conditioning produces significant variability in RH across building zones, with bedrooms consistently experiencing the highest sustained humidity levels. This reflects findings in residential buildings surveys where the bedrooms often show the greatest presence of interior surface mould (43).

Table 6: Key statistical measures of RH intermittent conditioning in CZ 21.

climate	Plan Ori.	Zone/Room	Wall Ori.	Max. RH	Min. RH	Avg. RH	RH > 70%
	North	Outdoor		100	7	64.6	+39.5%
		Kitchen, living	N, S, E	95.5	20.7	53.6	+8.7%
		Bathroom	W	85.0	10.5	49.1	+3.4%
		Bed 1	W, S	93.4	13.4	54.9	+14.7%
		Bed 2	W	92.5	14.3	53.5	13.1%
		Bed 3	N, W	93.0	13.6	53.1	+14.0%
		Bed 4	W	92.8	14.2	53.7	+13.2%
		Laundry	E	86.5	10.4	50.3	+4.2%
CZ64 (NCC CZ6)		En-suite	W	85.4	12.8	48.7	+3.2%
		Toilet	W	84.0	7.3	48.3	+2.9%
	East	Kitchen, living	S, E, W	90.6	19.3	54.2	+8.6%
		Bathroom	N	92.6	16.3	52.7	+12.7%
		Bed 1	W, N	93.4	1.9	54.0	+14.2%
		Bed 2	N	92.6	16.3	52.7	+12.7%
		Bed 3	N, E	93.1	14.7	52.4	+12.8%
		Bed 4	N	92.9	16.0	52.8	+12.8%
		Laundry	S	86.7	10.4	51.1	+4.6%
		En-suite	N	85.3	14.4	48.2	+3.2%
		Toilet	N	84.5	15.4	47.3	+2.9%

4.1.2 The RH results of CZ 64 (+CZ 62)

The results presented in Table 7 summarise key statistical measures of indoor RH under uncontrolled RH intermittent conditioning for a typical CZ 64 dwelling located in NCC CZ 6. The data are disaggregated by plan orientation (north and east), individual rooms or zones, and wall orientations, providing maximum, minimum, and average RH values, as well as the percentage of time RH exceeds 70%.

For the north-oriented plan, outdoor RH ranges from 10% to 100%, with an average of 74.1% and 64.1% of the time exceeding 70%. Indoor RH levels are generally lower, with the highest average RH observed in Bed 1 (59.3%) and the lowest in the En-suite (54.8%). Maximum RH values approach saturation in all rooms, particularly in the bedrooms and kitchen/living areas, which reach up to 99.7% RH. The proportion of time exceeding 70% RH varies substantially across spaces, with bedrooms consistently exhibiting high durations above this threshold (Bed 1: 21.4%, Bed 2: 19.6%, Bed 3: 20.3%, Bed 4: 19.8%), while service spaces such as the bathroom and laundry show lower percentages (Bathroom: 10.3%, Laundry: 13.0%).

In the east-oriented plan, a similar trend is observed. Maximum RH values remain close to 100% across the majority of rooms, with the highest values recorded in Bed 1 (99.6%) and slightly lower values in the bathroom (93.1%). Average RH levels range from 53.9% in the toilet to 59.4% in the kitchen/living area. RH exceedance above 70% follows a comparable pattern to the North orientation, with bedrooms again showing the highest values

(Bed 1: 21.1%, Bed 2: 19.2%, Bed 3: 19.5%, Bed 4: 19.6%) and service spaces remaining lower (Bathroom: 7.9%, Laundry: 14.1%).

Overall, the data indicate that under uncontrolled RH intermittent conditioning, all indoor zones experience periods of high RH, with bedrooms consistently showing both high peak RH and extended rates above 70%. This suggests that these spaces may be at greater risk of moisture accumulation and potential mould growth. The kitchen and living areas also exhibit prolonged high RH, whereas bathrooms, laundries, and toilets generally experience lower average RH and reduced exposure time above 70%. These results highlight the influence of room function and wall orientation on indoor hygrothermal condition.

Table 7: Key statistical measures of RH intermittent conditioning in CZ 64.

climate	Plan Ori.	Zone/Room	Wall Ori.	Max. RH	Min. RH	Avg. RH	RH > 70%
	North	Outdoor		100	10	74.1	+64.1%
		Kitchen, living	N, S, E	99.7	18.6	58.7	+17.3%
		Bathroom	W	92.9	15.2	55.9	+10.3%
		Bed 1	W, S	99.6	19.9	59.3	+21.4%
		Bed 2	W	99.0	15.2	58.0	+19.6%
		Bed 3	N, W	99.5	17.9	57.8	+20.3%
		Bed 4	W	99.1	14.9	58.2	+19.8%
		Laundry	E	94.6	17.0	57.5	+13.0%
CZ64 (NCC CZ6)		En-suite	W	93.6	18.1	54.8	+9.5%
		Toilet	W	90.5	14.3	54.6	+7.9%
	East	Kitchen, living	S, E, W	99.6	18.6	59.4	+17.5%
		Bathroom	N	93.1	18.4	53.9	+7.9%
		Bed 1	W, N	99.6	14.7	58.6	+21.1%
		Bed 2	N	98.9	19.1	57.6	+19.2%
		Bed 3	N, E	99.2	17.0	57.5	+19.5%
		Bed 4	N	99.4	19.6	57.7	+19.6%
		Laundry	S	95.3	18.1	58.2	+14.1%
		En-suite	N	93.7	17.9	54.4	+9.6%
		Toilet	N	91.2	18.4	53.9	+7.9%

4.1.3 *The RH results of CZ 66*

The data in **Table 8** are key statistical measures for indoor RH in the CZ 66, NCC CZ 4 & CZ 6. The data organized the same way as previous tables, the maximum, minimum, and average relative humidity, as well as the percentage of time the RH >70%.

Table 8: Key statistical measures of RH intermittent conditioning in CZ 66.

climate	Plan Ori.	Zone/Room	External Wall Ori.	Max. RH	Min. RH	Avg. RH	RH > 70%
	North	Outdoor		100	7	75.5	+64.1%
		Kitchen, living	N, S, E	100	18.6	55.6	+23.3%
		Bathroom	W	100	13	55.4	+13.4%
		Bed 1	W, S	100	14.8	57.0	+14.4%
		Bed 2	W	100	13	55.4	+18.1%
		Bed 3	N, W	100	14.2	54.9	+18.8%
		Bed 4	W	100	10.5	55.6	+17.9%
		Laundry	E	100	12.1	56.0	+12.4%
CZ66 NCC CZ4 &6		En-suite	W	100	13.31	51.4	+5.7%
		Toilet	W	98.1	8.7	53.0	+6.1%
	East	Kitchen, living	S, E, W	100	15.8	56.3	+10.6%
		Bathroom	N	100	12.7	53.3	+7.6%
		Bed 1	W, N	100	13.0	56.0	+19.4%
		Bed 2	N	100	15.4	54.7	+17.5%
		Bed 3	N, E	100	14.3	54.5	+17.4%
		Bed 4	N	100	15.6	54.7	+17.7%
		Laundry	S	100	12.1	57.1	+14.2%
		En-suite	N	100	14.3	50.8	+5.5%

	Toilet	N	95.7	14.7	51.6	+5.5%

For the house with a north-facing orientation, the Max. RH was consistently 100% across most indoor spaces. The Min. RH values for indoor rooms ranged from 10.5% (Bed 4) to 18.6% (Kitchen, living). The kitchen, living area registered the highest Avg. RH at 55.6% and the longest duration above 70% at +23.3%. Bed 2 and Bed 3 followed closely, with Avg. RH values of 55.4% and 54.9%, and corresponding exceedance percentages of +18.1% and +18.8%, respectively. Rooms like En-suite and Toilet demonstrated the lowest average humidity, with the En-suite recording the absolute lowest Avg. RH at 51.4% and the shortest duration above 70% at +5.7%.

The east-facing house demonstrated similar overall trends for RH, with Max. RH values also predominantly 100% across all rooms. The Min. RH values were slightly less dispersed than in north, ranging from 12.1% (laundry) to 15.8% (kitchen, living). The highest Avg. RH under Plan East was observed in the Laundry at 57.1%, which also exhibited the longest duration above 70% at +14.2%. The Kitchen, living area had the second-highest Avg. RH at 56.3% and an exceedance of +10.6%. Among the bedrooms, Bed 1 and Bed 4 recorded the highest Avg. RH at 56.0% and 54.7%, with exceedance percentages of +19.4% and +17.7%, respectively, suggesting high humidity loads in these spaces. Conversely, the En-suite and Toilet again showed the lowest average humidity values, with the En-suite registering the minimum Avg. RH at 50.8% and the toilet exhibiting the lowest exceedance percentage at +5.5%.

4.2 The hygrothermal results

Table 9 presents the simulated final water accumulation results in kg/m² of clay masonry veneer external wall system within assessed climate zones. The analysis commenced with a uniform initial water content of 1.38kg/m² in various assemblies. The first three column on the left are plan orientation, wall orientation and room names. The primary variables investigated include four distinct climates (CZ 21, CZ 64, CZ 66 of NCC-CZ 4, and CZ 66 of NCC-CZ 6) and the presence or absence of an interior vapour control layer, as listed in each column in purple.

Table 9: Hygrothermal Performance of clay masonry veneer wall system – Yes/No applies to cavity.

		Cavity –	Yes							
		Climate –	CZ21		CZ64		CZ66NCC4		CZ66NCC6	
		Exterior membrane –	Class 4-1 (175.4)		Class 4-1 (175.4)		Class 3-1 (1398)		Class 4-1 (175.4)	
		Interior vapour control –	No	Yes	No	Yes	No	Yes	No	Yes
Plan	Room	Wall								
N	KL	S	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bed1	S	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bed3	N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	KL	N	0.00	0.00	0.00	0.00	39.65	0.00	0.00	0.00
E	Laund..	S	0.00	0.00	0.00	0.00	2.52	14.43	0.00	0.00
	Bathro..	N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bed1	N	0.00	0.00	0.00	0.00	3.31	2.88	0.00	0.00
		S	0.00	0.00	0.00	0.00	0.00	3.25	0.00	0.00
	Bed2	N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bed3	N	0.00	0.00	0.00	0.00	0.00	34.17	0.00	0.00
	Bed4	N	0.00	0.00	0.00	0.00	0.00	1.80	31.04	0.00
	Ensuite	S	0.00	0.00	0.00	0.00	0.00	4.75	0.00	0.00
	KL	S	0.00	0.00	0.00	0.00	23.27	5.15	0.00	0.00
	Toilet	N	0.00	0.00	0.00	0.00	39.87	14.53	37.09	0.00

*The start water content is 1.38kg/m².

water accumulation
0.0 100.0

The results indicate that for scenarios in CZ 21 and CZ 64, no moisture accumulation occurred in any of the tested wall configurations, with cavity applied to all, regardless of the presence of an interior membrane. The final water content in these cases remained at or below the initial value. The legend on the top left indicates the level of moisture accumulation, the darked colour means higher water content.

In contrast, water accumulation was observed under CZ 66 NCC-CZ 4 and CZ 66 NCC-CZ 6, with this behaviour being predominantly associated with the presence of an interior vapour control layer. When an interior membrane was included (the "Yes" columns), water accumulation was eliminated in NCC-CZ6 across all rooms and orientations. However, the influence of the interior vapour control layer was not uniform across climate zones. In NCC-CZ 4, a few cases exhibited moisture accumulation when an interior vapour control layer was applied compared with cases without one. For instance, in the south-facing laundry wall under CZ 66 NCC-CZ4, water accumulation increased from no accumulation without an interior vapour control layer to 14.43 kg/m² with its inclusion. Similarly, in the north-facing Bed 3 wall of the east-oriented plan, accumulation increased from 0.00 kg/m² to 34.17 kg/m² following the addition of the interior vapour control layer.

The highest levels of water accumulation were recorded in both house plan north-facing and east facing, without an interior membrane. Under the CZ 66 NCC-CZ 4 scenario, the north-facing walls of the Kitchen/Living (KL) and Toilet rooms exhibited the most substantial moisture content, reaching 39.65kg/m^2 and 39.87kg/m^2, respectively. Under the CZ 66-NCC 6 scenarios, the plan east facing, north-facing walls of the Toilet and Bed4 rooms demonstrated the highest accumulation, with values of 37.09kg/m^2 and 31.04kg/m^2, respectively. These findings strongly suggest that the combination of specific climatic condition, different exterior vapour control layer and an interior vapour control layer poses statically significant results for interstitial moisture accumulation. Here, further studies would be required to understand the inconsistent performance of the applied interior vapour control layer and to investigate alternatives, such as vapour control layers with varying or humidity-controlled permeances.

Table 10 presents the hygrothermal analysis to assess the performance of CFCS wall assemblies, which commenced with an initial water content of 1.48kg/m^2. The structure of the table is similar to the previous one but includes the additional aspect of a ventilated cavity which is currently not required within the Australian building regulations. The results are presented in two primary configurations, distinguished by the presence or absence of cavity and interior vapour control layer. The dotted line in the middle separated the panel of no cavity on the left and with cavity on the right.

Consistent with the previous findings, the CFCS wall assemblies demonstrated no accumulation of water in the CZ 21 and CZ 64 inside the wall. However, in the more demanding CZ 66 NCC-CZ 4 and CZ 66 NCC-CZ 6 climates, the CFCS walls exhibited a pronounced vulnerability to interstitial moisture accumulation, which is greater than in the previously analysed clay masonry veneer system.

In the first primary configuration ("No cavity"), substantial water accumulation was recorded when the interior membrane was absent. The highest values were observed in the north-facing walls of the east-oriented house under the CZ 66 NCC-CZ 4 scenario, reaching 70.58kg/m^2 in Bed4 and 65.94kg/m^2 in Bed1. The inclusion of an interior control layer with a Class 4 exterior membrane mitigated this effect but increased in some cases if the Class 4 membrane was replaced by a less permeable Class 3 exterior membrane. However, there are also exceptions for example, the moisture content in the Toilet, Bed 4, Bed3 and Bed2 when house-oriented east, these walls water content increase from initial amount 1.48 kg/m^2 to 65.70, 70.58, 64.20 and 65.94kg/m^2.

The second primary configuration ("Yes"- with cavity), with even higher levels of moisture accumulation observed in all cases. The peak moisture content of the entire study occurred under this configuration: a north-facing wall in Bed 1 under CZ 66 NCC-CZ 4, which reached 91.16 kg/m² with an interior membrane. Similar to the no-cavity case, a Class 3 exterior membrane combined with an interior control layer tended to increase moisture content. When both the primary component and the interior membrane were present, the use of a Class 4 exterior membrane showed improvements in some cases. For example, under CZ 66 NCC-CZ 6, the east-facing KL wall (17.49 kg/m²), the south-facing KL wall, and the north-facing Toilet wall (26.64 kg/m²) all demonstrated reduced water accumulation. However, a few exceptions were identified again: specifically, the east-facing Toilet wall and Bed 3 wall showed increased moisture when both a Class 4 exterior membrane and an interior membrane were applied. Overall, the performance of the interior membrane remains complex and inconsistent. These findings indicate that, for CFCS assemblies in these climates, the risk of interstitial condensation remains high, particularly when multiple or unsuitable control layers are included, with the interior vapour control layer contributing to variable outcomes.

Table 10: Hygrothermal performance of CFCS wall systems.

		Cavity –	No								Yes							
		Climate –	CZ21		CZ64		CZ66NCC4		CZ66NCC6		CZ21		CZ64		CZ66NCC4		CZ66NCC6	
		Exterior membrane –	Class 4-1 (175.4)		Class 4-1 (175.4)		Class 3-1 (1398)		Class 4-1 (175.4)		Class 4-1 (175.4)		Class 4-1 (175.4)		Class 3-1 (1398)		Class 4-1 (175.4)	
		Interior vapour control –	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Plan	Room	Wall																
N	KL	S	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bed3	N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bed1	S	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	KL	N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E	Toilet	N	0.00	0.00	0.00	0.00	0.00	65.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15.60	22.22	26.64
	LDY	S	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	KL	S	0.00	0.00	0.00	0.00	11.34	4.90	4.61	15.57	0.00	0.00	0.00	0.00	19.94	73.84	17.49	0.00
	ENS	N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bed4	N	0.00	0.00	0.00	0.00	0.00	70.58	0.00	23.06	0.00	0.00	0.00	0.00	7.38	49.54	4.95	1.72
	Bed3	N	0.00	0.00	0.00	0.00	0.00	64.20	40.77	26.42	0.00	0.00	0.00	0.00	10.81	23.96	10.04	20.81
	Bed1	N	0.00	0.00	0.00	0.00	0.00	65.94	38.62	10.22	0.00	0.00	0.00	0.00	16.98	91.16	18.82	0.00
		S	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bed 2	N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bath	N	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

*The start water content is 1.48kg/m^2.

water accumulation: 0.0 – 100.0

4.3 The bio-hygrothermal results - Mould growth

To ensure consistency with previously validated indoor mould risk simulation studies, the Mould-growth Index (MI) system was adopted as the reference framework for assessing mould growth potential. In accordance with NCC 2022, a MI value greater than 3.0 is deemed unacceptable on the interior surface of the water control layer or on any building components located inward of this layer within roofs or external walls. This threshold also defined by AIRAH DA07, is essential for compliance with Performance Requirements F8P1 (Volume One) and H4P7 (Volume Two) and is critical for minimising the adverse health impacts of water vapour and condensation.

The MI scale from the VTT model (47), used for empirical validation, is defined as:

- $0 < MI \leq 1$: Small amounts of microscopic mould growth detectable on surfaces.

- 1 < MI < 3: Several localised colonies of microscopic mould growth present on surfaces, potentially visible as mould covering less than 10% of the area, or up to 50% coverage at the microscopic level.
- 3 ≤ MI < 6: Visible mould growth with high colonisation, covering more than 50% of the surface area.
- MI = 6: Very high and dense colonisation, with approximately 100% surface coverage (maximum rating in WUFI VTT).

Table 11 and **Table 12** presents the results for the MI. The legend in the top-left corner displays the MI values using three distinct colour scales: green indicate MI <1.0, grey is MI 1.0 to <3.0, and red is ≥3.0. To be clear, green and grey are both acceptable within NCC2022, red results are indicating unacceptable, further exploration is required. However, international research is increasingly recommending a simulated MI of <1.0, providing the reasoning for the three classifications shown in the table.

For the clay masonry veneer wall system in **Table 11**, the results for CZ 21 show that the MI remains below the 1.0. In CZ 64, several results yielded an MI of 0.75 to 6.0, 4 out of 28 cases, 14.2% fail to meet the NCC required 3.0. A key finding is that the application of the interior membrane resulted in a frequently higher MI, as all results fell within the red scale.

Table 11: Bio-hygrothermal Performance of clay masonry veneer wall system.

Mould Index (0.000 – 6.000)		Cavity –	Yes							
		Climate –	CZ21		CZ64		CZ66NCC4		CZ66NCC6	
		Exterior membrane –	Class 4-1 (175.4)		Class 4-1 (175.4)		Class 3-1 (1398)		Class 4-1 (175.4)	
		Interior vapour control –	No	Yes	No	Yes	No	Yes	No	Yes
Plan	**Room**	**Wall**								
N	KL	S	0.013	0.003	6.000	6.000	6.000	6.000	5.500	0.380
	Bed1	S	0.004	0.003	5.500	6.000	5.500	6.000	4.500	0.750
	Bed3	N	0.013	0.006	5.000	6.000	6.000	6.000	5.500	5.000
	KL	N	0.025	0.008	5.000	5.500	6.000	6.000	6.000	6.000
E	Laundry	S	0.001	0.001	5.500	6.000	6.000	6.000	6.000	6.000
	Bathroo..	N	0.005	0.005	3.000	5.500	2.500	6.000	0.300	4.500
	Bed1	N	0.015	0.003	5.000	5.500	6.000	6.000	6.000	6.000
		S	0.003	0.003	5.500	6.000	6.000	6.000	6.000	6.000
	Bed2	N	0.008	0.008	0.750	5.500	6.000	6.000	6.000	6.000
	Bed3	N	0.013	0.006	5.000	6.000	6.000	6.000	6.000	6.000
	Bed4	N	0.013	0.006	5.000	5.500	6.000	6.000	6.000	6.000
	Ensuite	S	0.003	0.004	3.000	5.500	6.000	6.000	6.000	6.000
	KL	S	0.013	0.003	6.000	6.000	6.000	6.000	6.000	6.000
	Toilet	N	0.003	0.004	2.500	5.500	6.000	6.000	6.000	6.000

In CZ 66-NCC 4, an MI of 6 was frequently observed, indicating a consistent failure to comply with the maximum permissible threshold of 3.0. Among the 28 evaluated cases without an interior membrane, only one case achieved an MI of 2.5, while all remaining cases exceeded acceptable MI values. In climate zone CZ 66-NCC 6 (the last two columns), 3 out of 28 cases yielded MI values at or below 3.0, whereas the majority ranged between 5.5 and 6.0.

When the interior membrane was introduced, performance inconsistencies were again evident. For the north-oriented house, Kl and Bed 1 showed MI values reduced from 4.5 or 5.5 to within 1.0. In contrast, for the east-oriented house, bathroom assemblies demonstrated worsened outcomes, with MI values ranging from 0.30 to 4.5.

These results indicate that additional design or control interventions are required to enhance system performance within these climate zones. Furthermore, as the maximum reportable MI in the WUFI-VTT framework is capped at 6, differentiation among cases that may have exceeded this threshold is not possible, thereby limiting the resolution of the analysis in the most severe scenarios.

Table 12 below presented the bio-hygrothermal results for the CFCS external wall system, varying performance across different climate zones. The table structure and legend are the same as precious CFCS table. The dotted line in the middle separated the panel of no cavity on the left and with cavity on the right. In CZ 21, all cases were consistently performed within the required parameters, with the MI remaining at or below 3.0 on the green scale. In CZ 64, the system largely met performance requirements, with only 4 out of 26 cases exceeding an MI of 3.0. Notably, the application of the interior membrane in this zone ensured these cases remained within the green scale, indicating full compliance with the performance requirement. In contrast, the system consistently failed to meet performance requirements in CZ 66, where majority of the cases recorded an MI of 6.0. Neither the introduction of a cavity nor the application of an interior membrane consistently served as effective mitigation strategies. Reductions in MI, and therefore consistent improvements in performance were not observed uniformly in this climate zone.

Table 12: Bio-hygrothermal performance of CFCS wall system.

Mould Index: 0.000 – 6.000

		Cavity –	No								Yes							
		Climate –	CZ21		CZ64		CZ66NCC4		CZ66NCC6		CZ21		CZ64		CZ66NCC4		CZ66NCC6	
		Exterior membrane –	Class 4-1 (175.4)		Class 4-1 (175.4)		Class 3-1 (1398)		Class 3-1 (1398)		Class 4-1 (175.4)		Class 4-1 (175.4)		Class 3-1 (1398)		Class 3-1 (1398)	
		Interior vapour control –	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Plan	Room	Wall																
N	KL	N	0.015	0.025	0.100	0.075	6.000	6.000	0.450	0.150	0.005	0.013	0.150	0.150	6.000	6.000	0.400	0.125
	Bed1	S	0.008	0.030	0.200	0.350	6.000	6.000	4.500	0.200	0.005	0.013	0.025	0.175	6.000	6.000	4.000	0.125
	Bed3	N	0.006	0.025	0.125	0.100	5.500	5.800	0.127	0.125	0.005	0.013	0.100	0.200	5.500	6.000	0.150	6.000
	KL	S	0.025	0.030	5.500	0.500	6.000	6.000	6.000	0.250	0.013	0.015	4.500	0.200	6.000	6.000	5.500	0.100
E	Bath	N	0.006	0.025	0.100	0.075	0.001	3.500	0.095	0.085	0.005	0.010	0.150	0.150	0.200	5.000	0.075	0.100
	Bed 2	N	0.006	0.025	0.125	0.100	0.002	5.500	0.150	0.125	0.006	0.013	0.210	0.200	0.400	5.500	0.150	0.115
	Bed1	N	0.006	0.025	0.125	0.100	6.000	6.000	6.000	6.000	0.005	0.013	0.200	0.200	6.000	6.000	6.000	6.000
		S	0.005	0.030	0.350	0.350	0.175	5.000	0.030	0.050	0.006	0.015	0.250	0.200	0.150	5.500	0.040	0.075
	Bed3	N	0.006	0.025	0.125	0.100	6.000	6.000	6.000	6.000	0.005	0.013	0.200	0.200	6.000	6.000	6.000	6.000
	Bed4	N	0.006	0.025	0.125	0.100	6.000	6.000	6.000	6.000	0.005	0.013	0.200	0.200	6.000	6.000	6.000	6.000
	ENS	N	0.005	0.025	0.100	0.075	0.005	5.500	0.127	0.125	0.004	0.010	0.150	0.150	3.500	5.500	0.150	0.125
	KL	S	0.100	0.030	5.500	0.750	6.000	6.000	6.000	6.000	0.015	0.015	4.500	0.200	6.000	6.000	6.000	6.000
	LDY	S	0.004	0.025	0.075	0.250	6.000	6.000	6.000	6.000	0.010	0.010	0.100	0.150	6.000	6.000	6.000	6.000
	Toilet	N	0.005	0.025	0.100	0.075	6.000	6.000	6.000	6.000	0.005	0.010	0.150	0.105	6.000	6.000	6.000	6.000

4. Comparison of continuous and uncontrolled RH conditioning

To further understands these results, they are compared to the results of the continuous conditioning scenario as follows:

- Scenario A: Continuous conditioning as prescribed by ASHRAE Standard 160 and DA07, where indoor temperature is maintained within controlled limits of temperature ≤ 21.1°C, and RH regulated ≤ 70%.
- Scenario B: Intermittent conditioning based on profiles calculated using AccuRate, reflecting a regulated intermittent conditioned temperature of ≤ 21.1 °C while allowing unregulated relative humidity fluctuations.

Figure 6 focuses on comparing both conditioning strategies, specifically looking at how the MI is affected across various spaces, building orientations, and climate zone parameters (indicated by the case names, e.g., CZ 21, CZ 66) of CFCS wall systems. The red dashed line at MI = 3.0 serves as a critical threshold, often representing the maximum acceptable point, as prescribed by NCC. The black-and-white diagonally hatched bar depicts the results of continuous conditioning for the south-facing wall. The colour bars follow the same coding as the floor plan. Hatched bars represent south-facing walls, while solid-coloured bars represent north-facing walls.

From left to right in each plot, the bars indicate the current construction code requirements followed by any additional mitigation measures, with all mitigations applied at the far right. "N" or "Y" denote the presence of a cavity, numbers 4 or 3 indicate the class of the exterior membrane, and 1 or 0 indicate whether an interior vapour control layer was applied.

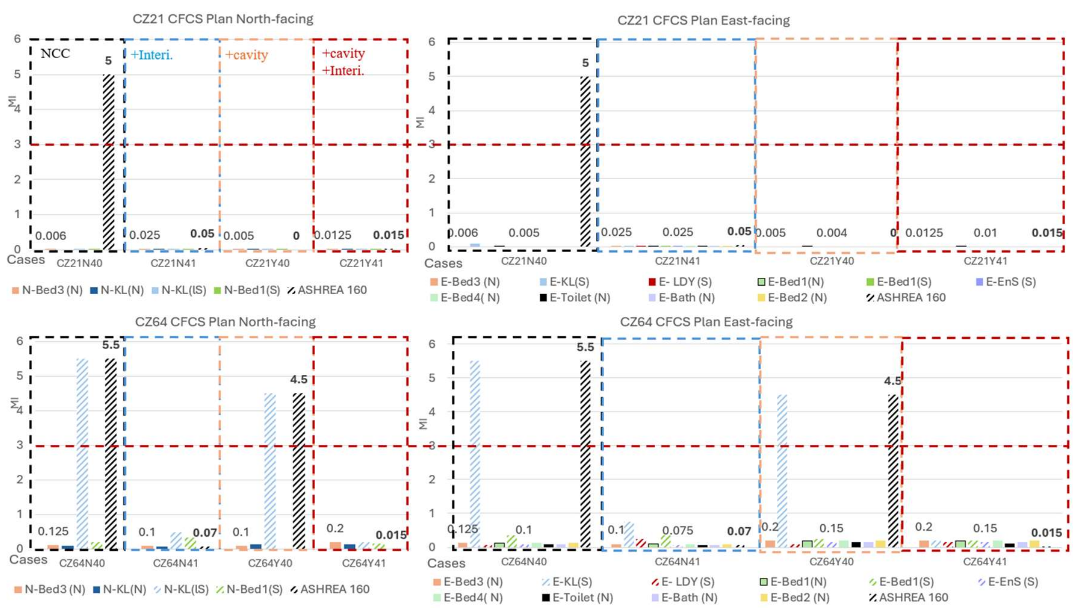


Figure 6: The Bio-hygrothermal results of CFCS in CZ 21, CZ 64.

The figure shows clearly that in CZ21, all the results of intermittent conditioning had MI less than 1.0, and continuous conditioning (according to ASHRAE) may result in MI up to 5.0. For the CZ64, most of the results of remain below 1.0 but the south facing open living wall shows the same predicted MI as under continuous conditioning. Upon applying both mitigation strategies, highlighted by the red rectangles, all data points align within the established acceptable benchmark of <1.0.

Figure 7 contains the results of CZ66, for NCC CZ 4 and CZ 6. For the first row of NCC CZ 4, a Class 3 exterior membrane was applied. When the house was north-oriented, the MI values were either comparable to or higher than the ASHRAE results, with all cases exceeding the failure threshold of 3.0. When the house was east-oriented, the results showed greater variability: some assemblies exhibited high risk, with MI values ranging from

5.5 to 6.0 in line with ASHRAE predictions, while others showed lower risk, with MI values below 1.0. Overall, approximately 60% of the cases exceeded the failure threshold of 3.0.

For the bottom plots of NCC CZ 6, a more permeable Class 4 exterior membrane was applied. The comparison between the ASHRAE-continuous conditioning results and the remaining uncontrolled RH intermittent scenarios shows a clearer distinction in bio-hygrothermal performance than observed in NCC CZ 4. The ASHRAE cases generally indicate very low moisture risk, with MI values clustered below the MI of 1.0 of both orientations. In contrast, the intermittent conditioning scenarios exhibit consistently higher MI values, with 50%-60% assemblies exceeding the ≥3.0 criterion.

Overall, the results indicate that the application of the continuous conditioning approach, as described in ASHRAE 160 and DA07, may underestimate mould growth risk for certain wall assemblies and operational conditions in this climate zone, reinforcing the need for broader indoor climate evaluation. Given the complexity of these results, closer examination of the scenarios based on other mitigation measures is needed. In the cases investigated here, most MI remained above 3.0 when typical mitigation methods were applied. Although the mitigation strategies effectively reduced the risk under continuous conditioning, the predicted MI value increased under intermittent conditioning with uncontrolled RH, resulting in poorer overall outcomes across the above categories. These findings indicate the need for further investigation to better understand the underlying mechanisms driving this behaviour.

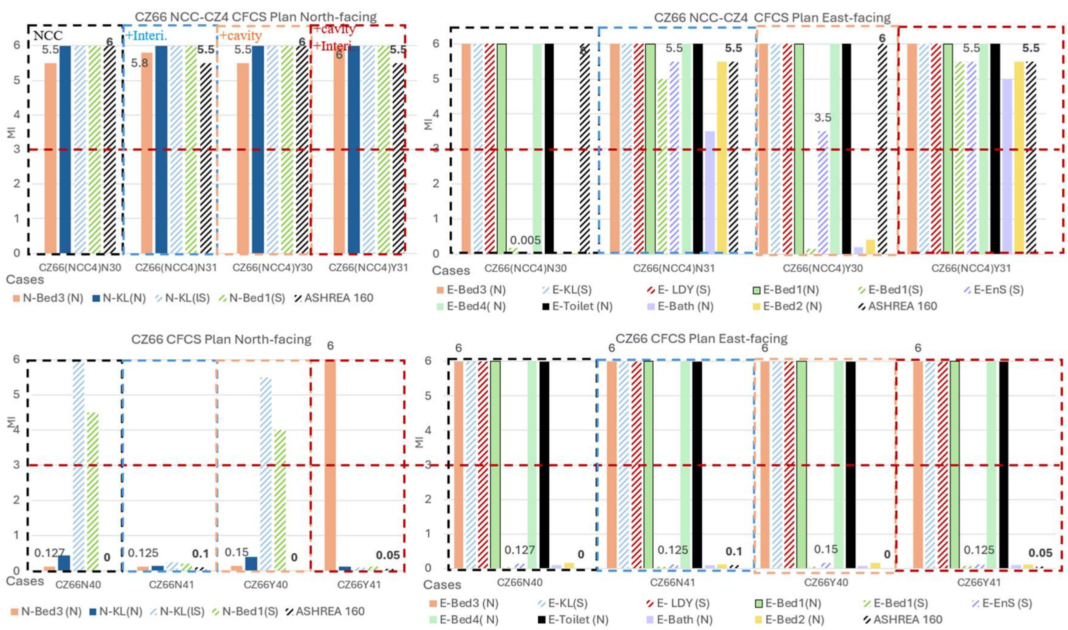


Figure 7: The Bio-hygrothermal results of CFCS in CZ66.

As illustrated in Figure 8, the clay masonry veneer wall system's performance also varied across climate zones. As the NCC mandates ventilated and drained cavities for clay masonry veneer walls, the interior vapour control layer is the only intervention applied. In CZ 21, the system consistently achieved a MI below the 3.0 threshold. These results were comparable to the ASHRAE-prescribed MI values, indicating no numerical significant difference between the two conditioning patterns.

Conversely, the results for CZ 64 exhibited greater variability than those observed in the preceding climate zones. For north-facing configurations, all cases consistently produced higher predicted MI values than their corresponding ASHRAE benchmarks, indicating elevated mould risk across all assemblies. In contrast, east-facing configurations demonstrated mixed performance, with approximately 72% of cases yielding MI values higher than those predicted by the ASHRAE assessment. Notably, in the lower right plot, the inclusion of the interior vapour control layer was unexpectedly associated with generally higher MI values. This suggests that, under the intermittent conditioning without RH control in CZ 64, the application of an interior vapour control layer may adversely affect hygrothermal performance, warranting further investigation into its interaction with orientation and operational conditions.

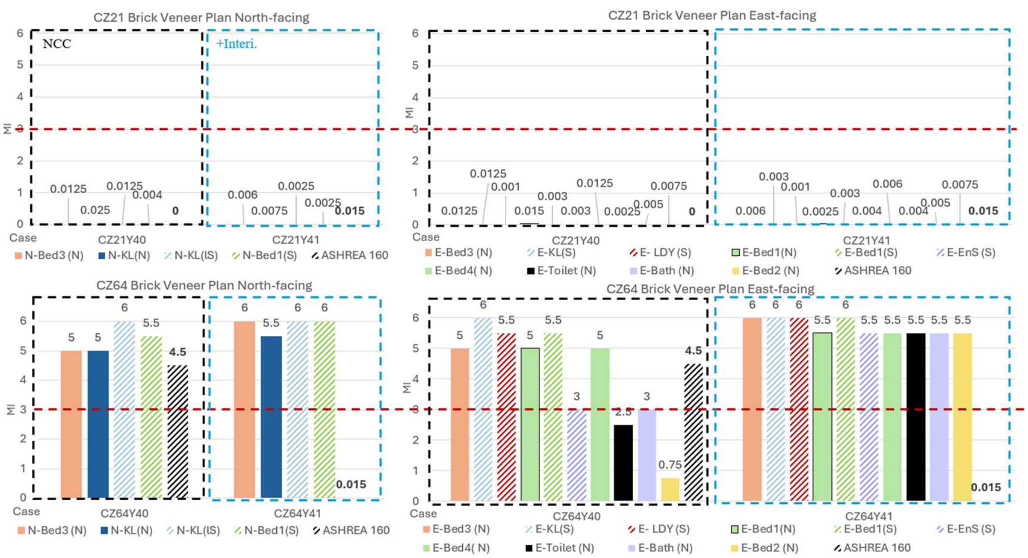


Figure 8: The Bio-hygrothermal results of clay masonry veneer in CZ21, CZ64.

In Figure 9, we can see the results of CZ 66 of both NCC CZ 4 and CZ 6. For NCC CZ 4 (the top two), MI values were consistently higher than the corresponding ASHRAE-prescribed MI benchmarks, which ranged from 5.5 to 6.0. Notably, all north-facing walls (indicated by solid fills) produced an MI value of 6, with the bathroom assembly being the only exception when the interior vapour control layer is not applied. The application of the interior vapour control membrane also demonstrated diverse effects. The inclusion of the interior membrane generally resulted in improved performance of both orientations under continuous conditioning, whereas for intermittent conditioning without RH control, it led to increased MI values.

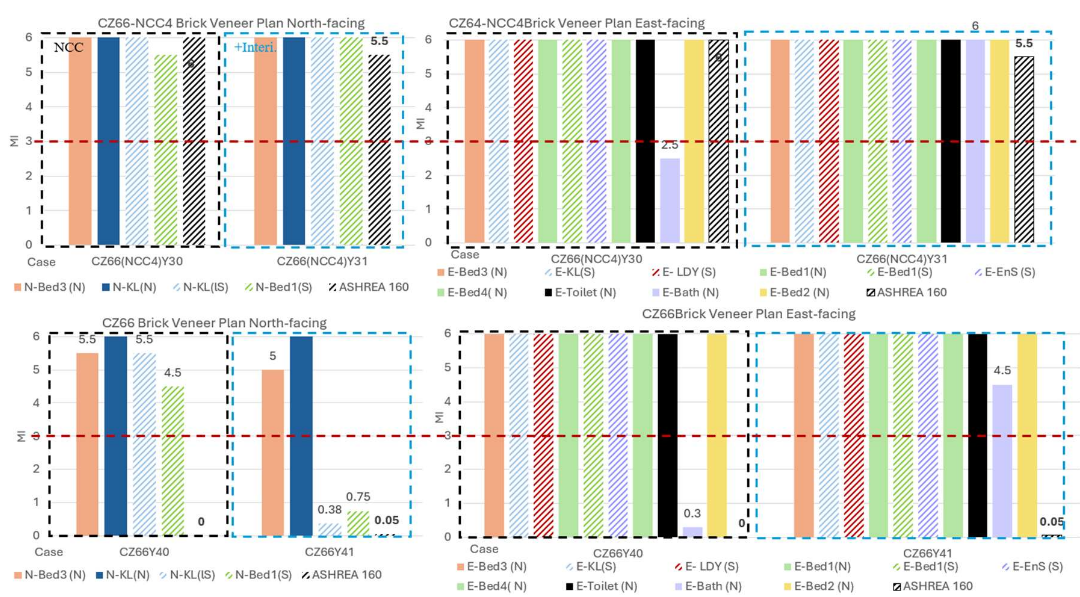


Figure 9: The Bio-hygrothermal results of clay masonry veneer in CZ 66.

For NCC CZ 6 (the bottom two), continuous conditioning resulted in negligible MI values, with all cases remaining below 1.0. In contrast, all other scenarios produced higher MI values than their corresponding continuous conditioning cases. In the bottom-left plot, where the house is north-oriented, the application of the interior vapour control layer generally reduced MI values in most cases, with the exception of the kitchen–living area (KL), which remained unchanged. However, in the east-facing scenarios shown in the bottom-right plot, most cases remained at an MI of 6.0, while the bathroom exhibited a marked increase in MI from 0.30 to 4.5 following the application of the interior vapour control layer.

Overall, the mitigation strategies demonstrated inconsistent performance across orientations and room types, indicating that the current interventions are insufficiently robust under intermittent conditioning without RH control. Further investigation is therefore required to identify mitigation measures that can reliably reduce mould risk under these conditions.

6. Discussion

The results of this study clearly indicate a statistically significant difference in moisture and mould risk under real-world conditions of intermittent conditioning without relative humidity control, compared with corresponding continuous conditioning scenarios. The findings also allow an evaluation of the clay masonry veneer and CFCS external wall system performance previous studies and their proposed mitigation measures (REF VBA reports). These results suggest that the impact of conditioning patterns and RH control has been underestimated, and that a gap exists between current moisture-management approaches prescribed in national and international guidelines and actual residential operating conditions.

More concerning is that mitigation strategies which have been approved as effective and promoted for future building design and construction do not consistently achieve the expected outcomes under realistic intermittent conditioning without RH control. This may result in higher construction costs while potentially increasing health risks. In particular, the application of the interior vapour control layer demonstrated highly inconsistent performance across different rooms, orientations, climate zones, and wall assemblies. These findings indicate the need for moisture-management guidelines that explicitly address conditioning patterns. Additionally, the research highlights the direct impact of uncontrolled room and orientation based interior relative humidity control. While more vapour-permeable exterior membranes showed relatively stable performance, further research is required to fully understand the behaviour of interior vapour control layers, cavities, and their combined application.

These results are unexpected, as conditioning patterns are often regarded as having a minor impact, yet their influence on building hygrothermal performance and indoor air quality appears to be substantial and underestimated. Mitigation strategies, particularly combined interventions incorporating interior vapour control layers, have previously been identified as among the most effective approaches to reducing moisture-related risks in building envelope systems. However, under intermittent conditioning without RH control, these strategies exhibited increased complexity and inconsistency, and in multiple cases were associated with worsened predicted MI values. These findings are in line with studies conducted in the UK and Australia, which reported that potential health risks in energy-efficient housing may arise from one or a combination of interacting variables (48,49). They also support the conclusion that a comprehensive evaluation of overall building performance is required. Previous research has also suggested that intermittent conditioning may contribute to indoor moisture accumulation and mould growth, and that conditioning operation influences both energy consumption (50–52), and indoor environment quality (53–55), Nevertheless, despite decades of emphasis on energy-efficient housing, research directly examining realistic intermittent conditioning and its impact on residential indoor environmental health has remained limited.

This study offers a perspective on energy-efficient building design in which energy savings must be considered alongside potential health risks. Ventilation remains a key factor in maintaining building resilience and ensuring acceptable indoor environmental quality (17,19,20,56). While intermittent conditioning may reduce energy consumption at both individual and national levels, its associated moisture-related risks require careful consideration.

This research applies a novel method to calculate indoor climate conditions representative of intermittent conditioning without RH control, contributing to improved understanding of long-term moisture-related risks in energy-efficient homes. Several limitations should be acknowledged. This research was limited to south-eastern temperate Australian climates and relied on material properties and mould sensitivity parameters assumed in the simulation, including the assumption of "perfect wall" construction, with no air or water leakage, and no construction failing. The intermittent conditioning schedules were based on Australian regulatory prescriptions, and indoor climate data were derived from generalised occupancy assumptions. Mould growth risk assessment was limited to a maximum MI of 6, whereas in practice mould growth may continue under favourable conditions. The ten years of simulation used a single reference meteorological year, and therefore longer-term climate variability and extreme events were not captured. In addition, due to limitations in AccuRate, moisture generation from showering was not included in bathroom simulations.

Further research should investigate how different conditioning patterns require specific moisture-management strategies. While the latest version of ASHRAE Standard 160 (2021) acknowledges that under intermittent conditioning relative humidity should not exceed 50%, this guidance remains high-level and insufficiently operational. More detailed criteria, performance thresholds, and practical design actions are required to translate this recommendation into effective moisture control strategies for energy-efficient residential buildings. For individual interventions, detailed building physics considerations are necessary, as no single solution is appropriate across all climates, materials, and operating conditions. This study recommends that future building moisture-management guidelines explicitly address intermittent conditioning scenarios. In the design of future energy-efficient homes, energy performance and indoor environmental health should be jointly considered in design and construction decision-making.

7. Conclusion

This study investigated the hygrothermal and bio-hygrothermal performance of typical Australian 7-Star NatHERS timber-framed clay masonry veneer and Compressed Fibre Cement Sheet clad external wall systems under intermittent conditioning without relative humidity (RH) control. Our findings reveal a critical divergence in performance between the intermittent conditioning without RH controlled profiles prevalent in Australian residential contexts which apply the continuous conditioning regimes prescribed by international standards such as ASHRAE 160 and adopted by DA07.

The results demonstrate that intermittent conditioning without RH control introduces unique risks for interstitial moisture accumulation and mould growth, particularly in cold-humid climates (CZ 66). Crucially, this research highlights that standard mitigation strategies, specifically the installation of interior vapor control layers may be counterproductive or even detrimental when subjected to uncontrolled RH and intermittent usage. While wall orientation and room functionality influence moisture dynamics, the primary driver of bio-hygrothermal risk is the synergistic interaction between local climate and specific operational conditioning patterns, further highlighting the needs for micro-climate and orientation informed simulation processes.

These findings expose a fundamental misalignment between current Australian building thermal performance and building conditioning regulations and the verification methods required to assess hygrothermal risks. The national and international drive toward airtight, high-performance envelopes often prioritize energy efficiency at the expense of moisture management. Beyond Australia, these findings serve as a critical alert for international standards: as climate warming increases and energy resources become more constrained, there is a broader shift from continuously conditioned to intermittently conditioned building interiors. , Secondly this research highlights the impacts of diverse climatic zones, from coastal to more inland based locations, with different diurnal conditions for location based temperature and relative humidity. By neglecting the impact of uncontrolled RH and dynamic occupancy, current guidelines significantly increase the risk of structural degradation and adverse health outcomes, directly undermining the objectives of resilient, net-zero construction.

To achieve true building high-performance, the focus must move beyond a singular focus on thermal energy and adopt an integrated moisture-risk framework. There is an urgent need for Australian building regulations, and those in other jurisdictions where intermittent conditioning is the cultural or economic norm, to formally incorporate RH management account for dynamic occupancy patterns, and more specific location based multi-year climate data. Future regulatory frameworks must prioritize a holistic balance, integrating energy efficiency with robust ventilation and advanced moisture control, to ensure that the transition to sustainable construction does not compromise the health and longevity of the global built environment.

Funding and Acknowledgement Statements

This research was supported by the Victorian Building Authority through a research grant in as-sociation with financial and project advisory committee support from Commonwealth Scientific and Industrial Research Organization, Master Builders Association of Victoria, Forest and Wood Products Australia, and Fraunhofer Institute for Building Physics.

Authorship Contribution

Liqun Guan: Principal author original draft, Methodology, Formal analysis, Conceptualization. Mark Dewsbury: Article review & editing, Method guidance and review, Supervision, Funding acquisition. Hartwig M. Künzel: Inputs and guidance of original draft, Article review & editing, Supervision. Louise Wallis: Supervision.

Data availability Statement

Data will be made available on request.

Declarations and Conflict of Interests Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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