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HYGROTHERMAL PERFORMANCE OF BUILDING ENVELOPES IN THE TROPICS UNDER OPERATIVE CONDITIONS: CONDENSATION AND MOULD GROWTH RISK APPRAISAL

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Graphical abstract

Abstract

Poor indoor hygrothermal performance increases the risk of indoor moisture problems and deterioration due to mould growth, corrosion and damage to archival materials. Hence, proper control of indoor thermohygric intensity abates indoor moisture and its associated problems. This paper presents the results of envelopes hygrothermal performance assessments in a hot and humid climate building with varying operational profile between adjacent spaces. The case-studied building runs on 24hrs cooling mode in one part against natural and/or mechanical supply-exhaust fan means on the other. In-situ experiments were combined with hygrothermal analytical methods to assess the envelope thermal quality together with the operative conditions against condensation and mould growth risks. The results show that the building is overcooled leading to poor envelope hygrothermal performance with associated condensation and mould growth problems on non-air-conditioned sides of the envelopes.

Keywords: Hygrothermal performance, building envelopes, condensation

Abstrak

Keupayaan hygrothermal yang tidak baik didalam bangunan akan meningkatkan masaalah kelembapan dalaman dan kemerosotan mutu disebabkan ketumbutan kulat, karat dan kerosakan kepada bahan. Oleh yang demikian kawalan terhadap kelembapan didalam bangunan adalah diperlukan. Kertas ini menerangkan keputusan dari penilaian keupayaan hygrothermal untuk banguan di kawasan cuaca panas dan lembab. Kajian kes adalah terhadap bangunan yang menggunakan sistem pengudaraan mekanikal dan semula jadi. Kajian di tapak dan analisa telah digunakan untuk menilai kualiti dan keadaan operasi bagi pencecairan dan penumbuhan kulat.Keputusan menunjukkan bahawa bagunan terlebih sejuk yang menjurus kepada keupayaan hygrothermal yang kurang baik terutama di kawasan yang menggunakan sistem penudaraan semulajadi.

Kata kunci: Keupayaan hygrothermal, dinding luar bangunan, pencecairan

1.0 INTRODUCTION

Poor hygrothermal performance in building remains a serious challenge to the occupants, stored components and building fabrics as prolonged cases leads to condensation, microbial proliferations and other associated issues. Such problems had continuously being a global challenge: about 4.2 million dwellings were reported as estimated values of UK dwellings with condensation and mould [1]. The view was upheld in the work of Clarke [2] which observed that large numbers of houses suffering from indoor mould growth. In financial terms, loss of productivity from such deterioration of the indoor microenvironment stands at an annual value of about 2.7 billion euros in Finland [3, 4]. As a results, moisture resistant building designs remains one of the major concerns for indoor air quality (IAQ) considerations [5].

Various sources of indoor moisture intrusion had been well documented [6-8]. Hygroscopic in nature, building materials maintain the moisture balance by absorption during elevated level and desorption when the ambient level drops – a phenomenon termed moisture buffering. Since moisture does not settle in vacuum, building surfaces from envelopes, furniture and other stored components become susceptible to elevated moisture beyond their moisture buffering value (MBV) [9]. Exceeding MBV leads to varying degrees of detrimental effects: IAQ, thermal discomfort, odour, microbial and other vermin proliferations, health hazards, and building materials' deterioration [10-12].

2.0 LITERATURE REVIEW

The quality of air in indoor environment tracks that of the outdoor ambient resulting in significant effects on IAQ, thermal comfort and energy efficiency [12, 13]. In the temperate climates, indoor spaces are operated at warmer temperature due to cold outdoor weather as against the tropical climate where the indoor environment operates on cold set-points due to warmer outdoor conditions. These opposing weather conditions lead to difference in vapour pressure on either sides of building envelope separating both indoor and outdoor environments. The variation in vapour pressure termed moisture balance or vapour pressure excess, had been successfully applied in temperate climates for indoor moisture investigations [14, 15]. Regardless of its success story in these regions, application of such approach in cooling mode, especially in the tropical climate buildings appear scanty.

In the tropics such as Malaysia, the air conditioning and mechanical ventilation (ACMV) systems play important roles in regulating the indoor hygrothermal conditions due to climate conditions characterized by high thermohygric conditions. In the report of Tang and Chin [16], the maximum/minimum values of hygrothermal conditions in Malaysia are given as 35.6°C/20.6°C and 100%/40% for temperature (T) and relative humidity (RH) respectively. T and RH remain important determining factors for microbial proliferations as well as human thermal comforts [17], their settings and control are equally important in energy savings of mechanical ventilation systems [18].

There is an increased need for energy efficiency measures in building design and operations due to high energy cost, near depletion of fossil based fuels and green house emission. Since the ACMV systems consume substantial amount of energy, different measures are employed to improve its energy efficiency on one hand and reducing both design and operative cost on the other. It is a practice to use plenum as return path in ACMV systems. In the tropical climate buildings, such approach had been known to pose no problem when most of the adjacent spaces are equally running on ACMV. In the recent events of energy efficiency measures in design and operations, building spaces are conditioned under varying operating profiles: some operates on 24-hrs basis, some on 8-hrs while some others are either naturally ventilated or served with mechanical supply-exhaust fan (MSEF) systems with non-conditioned outdoor air.

In the hot and humid climate, evidence exists of linking condensation problems with the practice of running some part of the microenvironment under cooling mode while adjacent spaces are either not in operations - 24hrs vs 8hrs [8, 19, 20] or rather being ventilated with unconditioned air by MSEF system [21]. Nevertheless, insufficient evidence exists on the building envelope thermal quality and the operative conditions over moisture related problems. It is against this background that the present study investigates the hygrothermal quality of building envelopes in a hot and humid climate building with mixed ventilations. The objectives is to investigate the envelope hygrothermal performance under the prevailing operative conditions against condensation and mould growth risks.

3.0 METHODOLOGY

3.1 Case Studied Building

The case studied building operates on a combination of constant air volume (CAV) ventilation systems on some parts against natural and/or mechanical supply-exhaust fan (MSEF) systems with no air-conditioning on others. The air distribution systems in individual spaces are mainly mixing type with the supply and return diffusers located on the ceiling levels [22-24]. The CAV system's air distribution is designed as a single duct where conditioned air is supplied to the downstream and return air through the ceiling plenum (Figure 1). In addition, the zones with limited occupancy are designed to be ventilated with MSEF systems with no air-conditioning. In terms of envelopes, the walls are made of 115 mm bricks finished with 15 - 20 mm rendering both sides with emulsion and weather resistant paint on the internal and external surfaces respectively. For the floor, the construction is made up of 150mm thick reinforced concrete slab finished in tiles with cement and sand backing. Additionally, acoustic ceiling tiles are used as ceiling finishes to divide the space into room and ceiling plenum zones.

Figure 1 shows a typical scenario in the case study building. The lower level space is designed as a CAV ventilated system while the upper space as MSEF system. In the CAV system, conditioned air from the air handling unit (AHU) is supplied (Sa) into the room via the supply diffuser and extracted (Ea) through the exhaust outlets. The extracted air is returned to the AHU through the ceiling plenum.

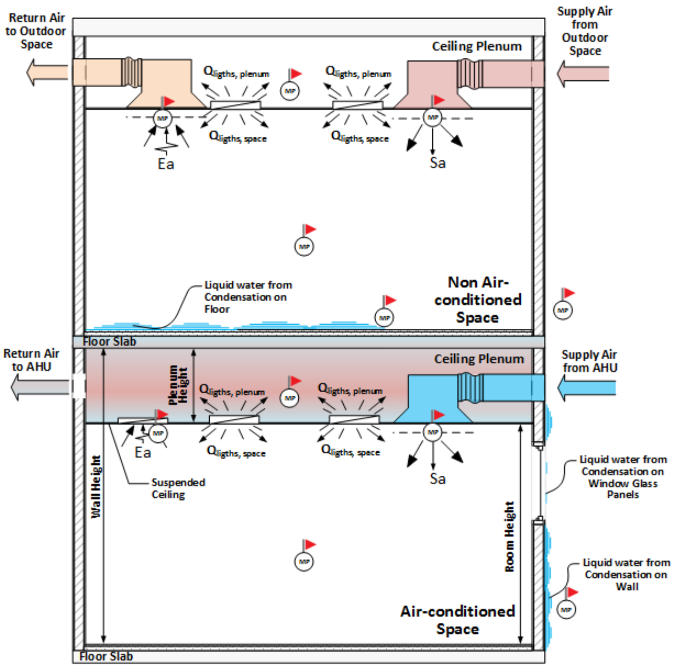

Figure 1 Diagrammatic representation of the Case Spaces showing the ventilation systems, the monitoring points and other related features

3.2 Instrumentation and Measurement

The study measures hygrothermal parameters over a period of one week during the month of May 2014. One week is considered adequate for the kind of assessment as found in earlier studies [12, 13, 25]. The

$$p_s = 610.5 \exp\left(\frac{17.269 \times \theta}{237.3 + \theta}\right), \qquad (for\ \theta \geq 0) \qquad (1)$$

month of May is found as the most critical month of the year for the test location with peak annual hourly external hygrothermal conditions (obtained from the nearby weather station) of T = 34.1 °C and RH = 100% for temperature and relative humidity respectively. Data were taken in both air-conditioned and non-air-conditioned spaces. Time-series data were measured with portable data loggers configured for automated logging at 10 minutes intervals. The measurement locations were supply and exhaust outlets, ceiling plenum, room ambient, and corridor spaces. In addition, a data logger is installed close to the floor of the space ventilated with MSEF systems sitting over CAV ventilated space.

Evidence exists of inherent errors and uncertainties in experiments for building performance diagnostics whether in the on-site or numerical ones Such uncertainty assessments, according to the studies, improves the reliability of the obtained results. The measuring equipment accuracy are ±0.5°C, T and ±3%, RH with precision 0.5°C, T and 0.5%, RH over a range of -35°C to 80°C, T and 0% to 100% RH. To further improve the data reliability, time-weighted average is employed as such, according to BSI [26], reduces measurement errors.

3.3 Envelope Hygrothermal Performance, Condensation and Mould Growth Risk

Indoor moisture formation depends on the hygrothermal interaction between the building envelopes and the ventilation systems [27]. Hence, improper coupling between them results in elevated indoor humidity and its consequential moisture related problems. Moisture moves from high to low vapour pressure regions and as such envelope moisture problems in the temperate climate appears on the warmer interior sides. Contrastingly, in hot and humid climate, the envelopes are susceptible to moisture formation on the warmer exterior sides. In essence, the distinction between the operative conditions in the temperate and tropical climate creates a reversal of the moisture movement direction. Against these assumptions, this study applied a modified approach for envelope hygrothermal quality assessments described in the literature [6, 28].

The study defines vapour pressures p_c and p_w for the cold (conditioned) and warm (unconditioned) sides of the envelopes respectively. In-situ hygrothermal data obtained from the time-series measurements were used to calculate the vapour pressure on both conditioned and non-conditioned sides. Equations (1) to (6) were adapted from the specifications in CIBSE [6] and BSI [28]. In the original context under temperate weather condition, notation i indicates the warm (indoor heated side) and e, cold (outdoor side). This study modifies the notation to suit application in the tropical climate buildings. Hence notation “c” indicates the cold (indoor conditioned side) and “w” warm (indoor unconditioned side).

Values of saturated vapour pressure (p_s), vapour pressure on cold side (p_c) and vapour pressure on warm side (p_w) are evaluated from the hourly hygrothermal parameters obtained in the time-series measurements using equation (1) and (2).

$$p = p_s \times \varphi \qquad (2)$$

In addition, the study adopts the recommended critical relative humidity (φ_{crit}) of 80% [6, 7, 28]. φ_{crit} is defined as the surface relative humidity that leads to surface deterioration (condensation, corrosion, mould growth, etc.). This critical humidity is defined as water activity, a_w in other studies and reports [29, 30].

$$p_s(\theta_{sw}) = p_w / \varphi_{crit} \qquad (3)$$

From the (φ_{crit}) and p_w an estimate is made of the minimum acceptable saturation vapour pressure, $p_s(\theta_{sw})$ at the envelope warmer side using equation (3). Subsequently, the minimum acceptable surface temperature (θ_{sw}) on the warmer side is evaluated – equation (4).

$$\theta_{sw} = \frac{237.3 \ln\left(\frac{p_{s(\theta_{sw})}}{610.5}\right)}{17.269 - \ln\left(\frac{p_{s(\theta_{sw})}}{610.5}\right)}, \left(for\ p_{s(\theta_{sw})} \geq 610.5\,Pa\right) \qquad (4)$$

The study further defines two parameters for envelope thermal quality: (a) thermal quality due to operative condition ($fR_{sw,op}$) – equation (5) and (b) thermal quality due envelope configuration and overall thermal transmittance ($fR_{sw,U}$) – equation (6). An envelope of $fR_{sw,U}$ greater than $fR_{sw,op}$ is of good hygrothermal quality and will provide high resistance to moisture formation. On the contrary, when $fR_{sw,U}$ is less than $fR_{sw,op}$, the envelope fails hygrothermal quality assessment and hence would be susceptible to surface condensation.

$$f_{Rsw,op} = \frac{(\theta_{sw} - \theta_c)}{(\theta_w - \theta_c)} \qquad (5)$$

$$f_{Rsw,U} = 1 - UR_{sw} \qquad (6)$$

Mould growth risk assessment methodologies had been evidently studied and documented [31]. This study adopts the formula presented in [32] where mould growth risk potential m was defined by equation (7).

$$m = \frac{\varphi}{\varphi_{crit}}$$

$$\phi_{crit} = \begin{cases} 100\%, & \theta \leq 0°C \\ -0.00267\theta^3 + 0.160\theta^2 - 3.13\theta + 100, & 0°C \leq \theta \leq 20°C \\ 80\%, & \theta > 20°C \end{cases} \qquad (7)$$

The parameters in equations (1) through (6) is defined as: p_s = saturated vapour pressure (Pa), p_v = air vapour pressure (Pa) (subscript *v* can be modified to *c* and *w* respectively for conditioned and non-conditioned spaces), p_a = atmospheric pressure of moist air (Pa), θ = measured temperature (°C), φ = measured relative humidity (%), φ_{crit} = critical relative humidity (%), $p_s(\theta_{sw})$ = saturated vapour pressure at minimum surface temperature (warm side) to prevent condensation (Pa), θ_{sw} = minimum surface temperature (warm side) to prevent condensation (°C), U = envelope thermal transmittance (W/m^2.K), R_{sw} = surface heat transfer coefficient on the warm side (m^2.K/W).

The methodology is applied to the measured data and results is as presented in the next section. Optimisation in building performance assessments provides a means of testing various design and operative condition options with the resultant effects on the building in whole or parts. Such hygrothermal performance optimisation was described in an earlier study by Moon, et al. [5].

4.0 RESULTS AND DISCUSSION

4.1 Indoor Operative Conditions

This study assessed the air conditioning system's operative conditions together with the overall hygrothermal performance of the building envelopes. It is revealed that the average diurnal thermal and hygric profiles are θ = 17.3 ±0.1°C, φ = 71.5 ±0.6%, and θ = 23.6 ±0.4°C, φ = 93.2 ±1.6%, respectively for the air-conditioning and non-air-conditioning space on either sides of the wall. The thermohygric profile between the plenum and the non-air-conditioned space above the room were found as: θ = 18.1 ±0.1°C, φ = 68.8 ±0.9%, θ = 25.8 ±0.4°C, φ = 85.4 ±1.9%.

These results revealed that variations in the field measurement for thermal and hygric data falls within the accuracy of the measuring equipment (θ = ± 0.5°C, φ = ±3%). This, similar to an earlier submission in Majeed [34], suggests that variations in the obtained data are due to factors other than the measuring equipment errors

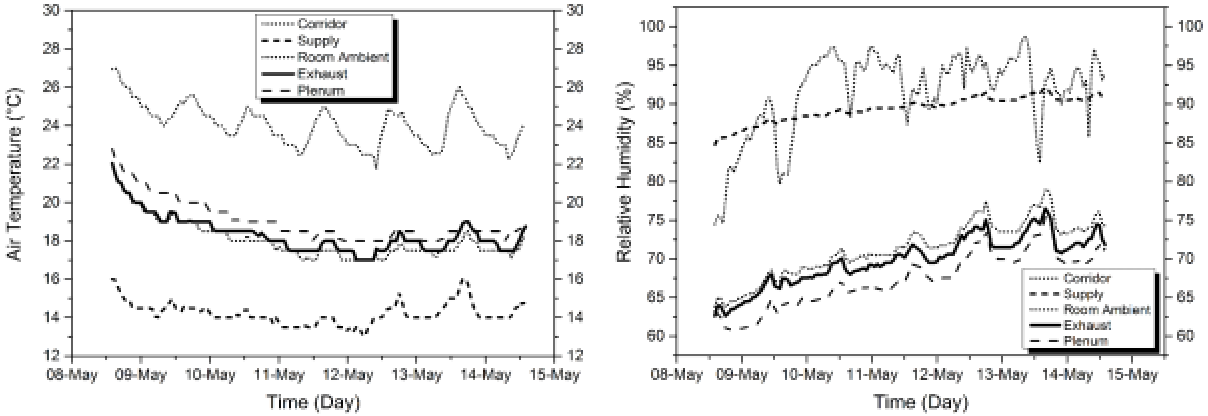

Figure 2 Hygrothermal profile in air-conditioned space (a) air temperature (b) relativity humidity

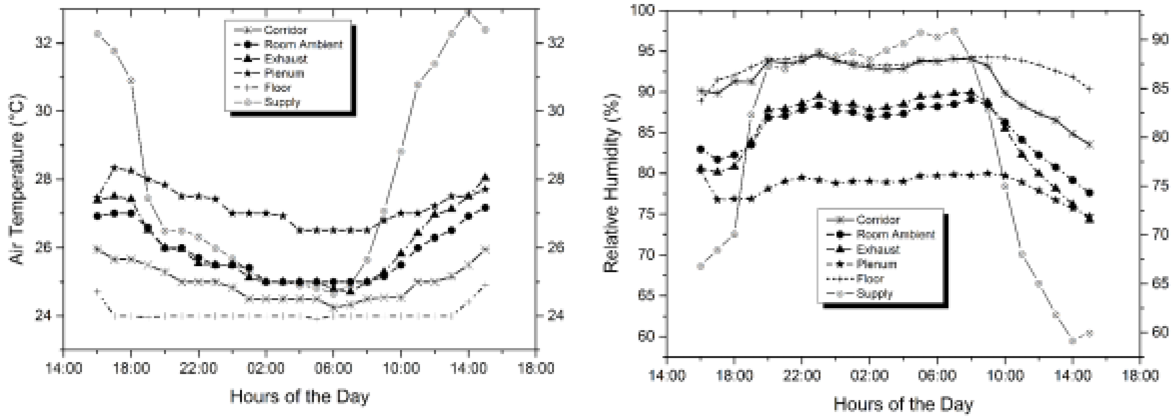

Figure 3 Hygrothermal profile in non-air-conditioned space (a) air temperature (b) relativity humidity

In terms of the operative conditions of the cooling systems, the results revealed an out of specification performance MS1525:2007 [35] (θ = 23 - 26°C and φ = 50 - 70%). The operative conditions affirmed an overcooling of the indoor environment, a result that supports a recent finding by Sekhar [36] that buildings in the hot and humid climates are overcooled. The overcooling condition could be attributed to moisture problems being witnessed in the building.

We plotted the time-series of time against microclimatic parameter values (θ and φ) for both the CAV and MSEF ventilated spaces (Figure 2 and 3). It is observed (Figure 2a) that the cooling system runs on 24hrs throughout the measuring period as the thermal profile of the supply air operates between 13.5 °C and 16.5 °C. A uniform air distribution is observed in the room from the ambient and return air profile that track each other throughout the investigation period (Figure 2a). Figure 2b revealed an elevated humidity in the supply air conditions as values ranges between 85.0% and 92.5%. This suggest a malfunction in the operative conditions of the cooling system in its dehumidification efficiency.

Figure 3 revealed elevated hygrothermal profile on the non-air-conditioned corridor, an evidence showing the humid nature of the test environment. The MSEF supplies unconditioned air at high temperature (T > 32 °C) and relative humidity (RH > 90%). Figure 4 revealed the effects of plenum return system on the upper room ventilated with MSEF system. The figure shows the dew point profile of the room ambient and air close to the floor. It was found that the surface temperature of the floor operates below the dew point of the ambient air near the floor.

Condensation occurs when the surface relative humidity reaches 100 percent or the surface temperature falls below the dew point temperature of the ambient air [37, 38]. The effects of floor surface temperature falling below the ambient air dew point is recorded as localized flood on the floor siting above plenum return air-conditioned space (Figure 5).

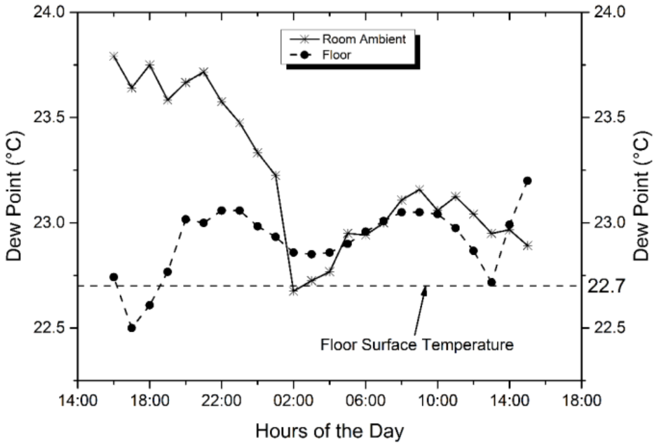

Figure 4 Hygrothermal Profile in non-air-conditioned space showing dew point of room ambient air and floor surface temperature

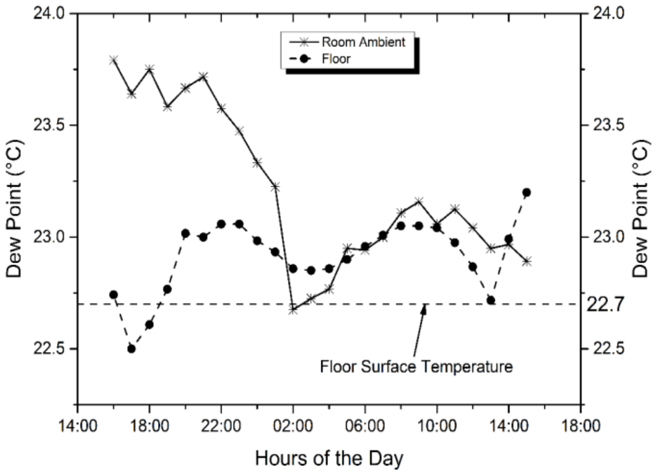

Figure 5 Hygrothermal Profile in non-air-conditioned space showing dew point of room ambient air and floor surface temperature

It can be seen from Figure 6 that condensation on floor in non-air-conditioned spaces siting over plenum return air-conditioned space.

Figure 6 Condensation on floor in non-air-conditioned spaces siting over plenum return air-conditioned space

4.2 Envelope Hygrothermal Quality and Condensation Risk Assessment

The study presents results of hygrothermal investigations through applications of the methodology proposed in ISO 13788-2012, CIBSE (2006) and ISO 15026 (2011) as described in equations 1 to 7. Table 1 gives a summary of the findings from the envelope hygrothermal performance investigation. Figure 7 and Figure 8 present the components of the wall and floor separating the air-conditioned from non-air-conditioned space together with the average operating conditions. Under the existing hygrothermal differential between the cold (conditioned) and warm (non-conditioned) spaces, the envelope (wall) thermal quality due to operative condition performed poorly ($fR_{sw,op}$ = 1.413) against the thermal quality due envelope configuration and thermal transmittance ($fR_{sw,U}$ = 0.709), thereby resulting in failure of the wall to meet up with the surface condensation criteria under the operative conditions. Similarly, the results of envelope performance for floor revealed $fR_{sw,op}$ = 1.149 and $fR_{sw,U}$ = 0.705 - an evidence depicting failure of the floor to satisfy the surface condensation criteria under the plenum return ventilation. As earlier stated and envelope with $fR_{sw,U}$ greater than $fR_{sw,op}$ appears of good hygrothermal quality and will provide high resistance to moisture formation. On the contrary, when $fR_{sw,U}$ is less than $fR_{sw,op}$, the envelope fails hygrothermal quality assessment and hence would susceptible to surface condensation.

Table 1 Results of hygrothermal performance assessment of building envelopes and operative conditions

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Envelope Type	***θc (°C)***	***φc (%)***	***θw (°C)***	***φw (%)***	***Δp (Pa)***	***$\theta sw,min$ (°C)***	***$fRsw,op$***	***$fRsw,U$***
Wall	17.3	71.5	23.6	93.2	1302.3	26.2	1.413	0.709
Floor	18.1	68.8	25.8	85.4	1409.9	26.9	1.149	0.705

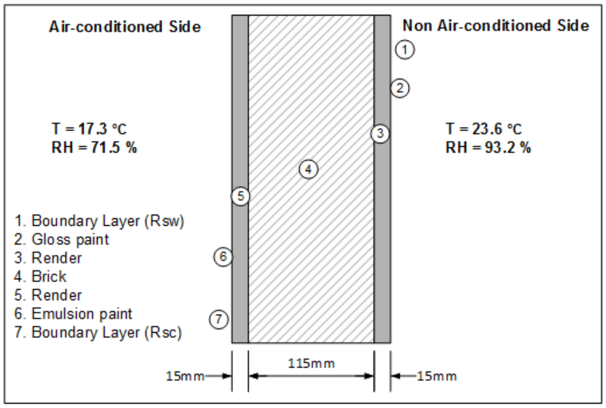

Figure 7 Existing Wall Components: Single Brick Wall

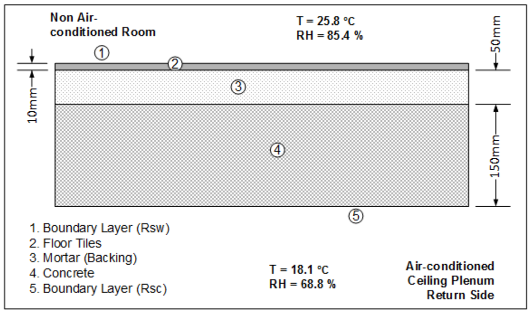

Figure 8 Existing Suspended Concrete floor above Ceiling Plenum Return space

4.3 Mould Growth Risk Assessment

The study further assess the mould growth risk, *m*, using equation (7). The average hourly mould growth potential during the measurement period for the plenum and floor surfaces of the upper (non-air-conditioned) is between 0.9 and 1.1 respectively. In addition, the *m-value* for the cold and warm surfaces of the wall was estimated at 0.9 and 1.2 respectively. Figure 9 presents the hourly profile of mould growth potential on the non-air-conditioned spaces.

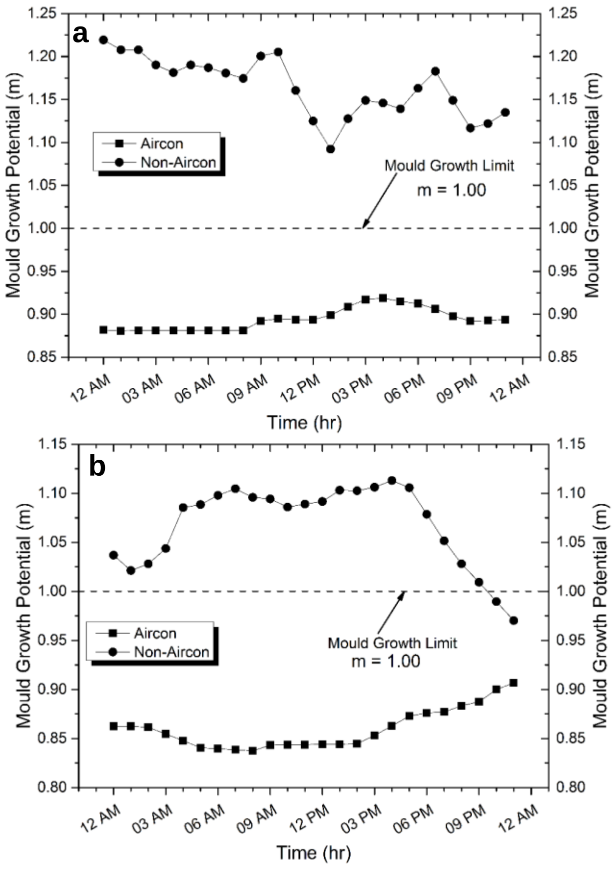

Figure 9 Hourly Profile of Mould Growth Potential on the Surfaces facing non-air-Conditioned Spaces (a) Wall (b) Floor (mould growth is possible during periods when m-value > 1.0)

As mould growth potential increases with *m-values* greater than 1 [32], it then implies that growth is possible on the upper floor and wall surfaces facing the non-air-conditioned spaces. These findings further suggest that overcooling conditions in CAV systems with plenum return ventilation is dangerous for the adjacent spaces are either naturally or MSEF system ventilated. These findings further suggest that overcooling conditions in CAV systems with plenum return ventilation is dangerous for the adjacent spaces are either naturally or MSEF system ventilated.

4.3 Discussion

In most period during the investigation, the hygrothermal gradients between the conditioned and non-conditioned spaces coupled with the hygrothermal quality of the building envelope result in lower surface thermal performance of the wall and floor facing the non-air-conditioned spaces. Consequentially, this led to a drop in the surface temperature below the dew point temperature of the ambient air and hence condensation. Interestingly, the floor and wall surfaces are finished in tiles and anti-fungal paints which contain less nutrient. Hence mould growth on the surfaces becomes impossible. This never solve the problems as condensed water evaporates and buffered (absorbed) by the porous building materials in the room (ceiling tiles, wood furniture, cardboard, etc.). More so, the potency of chemicals in anti-microbial finishes becomes reduced in prolonged damp conditions. Operation of the system in this mode resulted in continuous production of moisture. Moisture buffering by the porous materials cease when maximum water retention level is reached hence the material becomes saturated and moist. Materials with cellulose or other organic compounds therefore suffered from microbial growth while anti-microbial finishes loss their protective capabilities (Figure 10).

Figure 10 Deterioration due to Condensation and Moisture problem: (a) Microbial Growth on Ceiling and (b) Failure of Paints on Walls

5.0 CONCLUSION

The study investigates the building envelopes hygrothermal performance assessments in a hot and humid climate building with varying operational profile between adjacent spaces. The case-studied building runs on 24hrs cooling mode in one part against natural and/or mechanical supply-exhaust fan means on the other. Time-series measurements of microclimatic parameters were obtained in air-conditioned and non-air-conditioned indoor microenvironments: occupied zones, supply and exhaust openings, ceiling plenum and corridor. We adapted a methodology previously employed in temperate climates for building envelopes to assess the envelope thermal quality in relation to condensation and mould growth risks. The results revealed that the building is overcooled thereby contributing to the moisture problems in spaces above plenum ventilated space as the floor failed the criteria for surface condensation as well as mould growth risk assessments under the prevailing operative conditions. The results is similar for the wall separating the air-conditioned and non-air-conditioned space. Improvements can be achieved through optimisation of envelope hygrothermal quality and operative conditions as presented in a companion paper. Therefore, with the weather conditions in the tropics, it is imperative to affirm the building envelopes hygrothermal quality as well as operative set-points of the cooling systems before embarking on energy efficiency scheduling of mechanical ventilation systems under mixed operations. This will further enhance the sustainable operations of facilities in these region thereby creating buildings that are healthier to the users, the envelopes, the stored components and the environment at large through energy efficiency operations.

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