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Moisture condensation on building envelopes in differential ventilated spaces in the tropics: quantitative assessment of influencing factors

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Abstract. Ventilation systems play a significant role in maintaining the indoor thermal and hygric balance. Nevertheless, the systems had been implicated to result in many problems. In the tropical climate, especially for energy efficiency purposes, building spaces are operated with differential ventilation. Such spaces operate on 24-hrs basis, some on 8-hrs while others are either naturally ventilated or served with mechanical supply-exhaust fan systems with non-conditioned outdoor air. This practice had been found to result in condensation problems. This study involves a quantitative appraisal of the effect of operative conditions and hygrothermal quality of building envelopes on condensation risk. The in-situ experiment is combined with an analytical approach to assessing the hygrothermal quality of building envelopes in a tropical climate building under differential ventilation between adjacent spaces. The case-studied building is with a known history of condensation and associated damages including mould growth. The microclimate measurement and hygrothermal performance of the wall and floor against condensation and mould growth risks had been previously reported elsewhere. As a step further, the present study evaluates the effects of various envelope insulation types and configurations together with the HVAC cooling set-points on envelope hygrothermal performance. The results revealed that overcooling the air-conditioned side increases condensation risk on the non-air-conditioned side of the envelopes. The envelopes failed criteria for surface condensation at existing operative conditions irrespective of envelope hygrothermal quality improvements. However, the envelope performed well at improved cooling operative conditions even at existing envelope hygrothermal quality. It is, therefore, important to ascertain the envelope hygrothermal quality as well the cooling operative conditions while embarking on energy efficiency operations in mechanical ventilation systems under differential ventilation.

1 Introduction

Sequel to the aftermath of energy crisis coupled with the challenge of climate and fuel security, the need for building energy efficiency had reportedly been on the increase over the years [1-3]. Achieving energy efficiency in buildings had resulted in strict regulations on building envelope insulation and efficient heating ventilation and air conditioning (HVAC) systems [4]. Envelope insulation provides resistance to heat transfer between the indoor and outdoor environment of a building. A suitable insulation material isolates the indoor environment from thermal gradients by retaining or preventing heat from going out or coming into the building to respectively reduce the heating and cooling load of a building. To this end, the use of insulation had resulted in energy efficient improvement with the resultant HVAC energy consumption reduction [5, 6]. Nonetheless, many detrimental effects had been reported

as envelope insulation contributes to problems of moisture condensation and mould formation [4]. The reported moisture condensation risk can be explained from the submission of Johansson [7] where their study reiterated that envelope insulation yields different moisture content in the insulated wall. As moisture formation precludes mould growth, the risk of mould proliferation increases with moisture formation. A previous study by Van Loo *et al.* [8] found that some insulation materials (e.g., fiberglass) may serve as a support matrix for debris (nutrients for mould) collection such that when moisture forms on them can lead to mould growth.

Also, the HVAC) systems maintain the indoor air quality and thermal comfort through its regulation of the operative conditions. In the tropical climate, the system keeps the indoor environments below the outdoor elevated thermal and hygric profiles. As both temperature

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and relative humidity are significant environmental factors for human thermal comfort [9, 10], they are reported as being critical to the hygrothermal performance of building envelopes [11-13]. Maintaining the required level of indoor thermal comfort by the HVAC systems require high energy outlay which is attributively contributing to higher building sector energy consumption [14-16]. Also, the poor hygrothermal performance of building envelopes is found to have detrimental effects on the IAQ and energy efficiency [17-19]. Consequentially, the need for energy efficiency and IAQ improvements had led to the emergence of sophisticated HVAC systems and building envelopes with enhanced performance. The detrimental effects of building envelope insulation and HVAC systems to achieve building energy efficiency has continuously been the subject of concern over the years.

In a field trial to assess the performance of different roof constructions in a warm climate on indoor thermal comfort, Özdeniz *et al.* [20] found that the inclined roof constructions over concrete ceiling recorded acceptable performance. Nevertheless, moisture accumulation is prominent in this type of constructions. The author thereby concluded that air conditioned buildings in a warm climate are susceptible to condensation risk. This further underscores the associated moisture condensation risk with improved envelope insulation despite its energy efficient benefits. The overall energy savings is affected by the location of envelope insulation either on the internal or external faces. The studies of Kolaitis *et al.* [21] on envelope insulation and energy efficiency reported about 8% improvement in the performance of external insulation over the internally applied insulation. Also, on moisture condensation, the study found that the risk of condensation increases in internally applied insulation in a temperate climate. The findings on internally applied insulation and moisture problem can be associated with the warm indoor environment. The reverse of this case is related to warm climate as described in [22]

Despite the wealth of knowledge on the subject of HVAC systems, building energy efficiency, envelope insulation, and moisture problems, limited consideration exists for such review of both HVAC system operations and building envelope hygrothermal performance especially in the hot and humid climate of Malaysia. For instance, in the temperate climates, indoor spaces are operated at warmer temperature due to outdoor cold weather. On the contrary, the tropical climate indoor environment operates on cold set-points due to warmer outdoor conditions. The different microclimate on either side of building envelopes creates differential vapour pressure on opposing sides of the envelopes separating the indoor and outdoor environments in both temperate and tropical climates. While the effects had been well studied in the temperate climates resulting in various moisture investigations [23, 24], leading to the development of assessment methods [11-13, 25], tools [26] and envelope materials [27, 28], little exists on such considerations for the tropical climate buildings. With the increased energy efficiency need in building design and operations, there is a need to improve HVAC energy

efficiency. Differential ventilation is adopted where building spaces are conditioned under varying profiles: some systems operate on 24-hrs basis, some on 8-hrs while others are either naturally ventilated or served with mechanical supply-exhaust fan systems with non-conditioned outdoor air. Evidence exists on 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 [29-31] or rather ventilated with mechanical supply-exhaust systems with unconditioned air [32]

From the foregoing, there appears to be a synergistic relationship between HVAC energy consumption, building energy efficiency, insulation and above all moisture condensation problem. Although optimising insulation thickness is found to be an efficient way of providing energy savings [5, 6, 33], limited methods exist in the synergistic combination of insulation location (interior or exterior), insulation thickness, energy conservation and hygrothermal (moisture condensation, mould growth, etc.) risk [34]. This further suggests the needs for further studies on the combined effects of varying factors on hygrothermal performance of building envelopes

The problems above motivate our investigations into the envelope thermal quality under HVAC operative conditions against condensation and mould growth risks in the hot and humid climate buildings. To achieve these, we adapted a previous analytical method being used in temperate climates. Details of the fundamentals of such analytical methods for condensation assessment is documented CIBSE [25] and European [13] standards. In our initial attempt to adapt the methodology for tropical climate conditions, reported elsewhere [35], we found that 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 to prevent condensation and mould growth. The present studies build on the initial findings by investigating the effects of various insulation types and thicknesses coupled with the HVAC cooling conditions on envelope hygrothermal performance against condensation problems. It combines in-situ experiments with an analytical approach to assessing the building envelopes' hygrothermal quality under differential ventilation of air-conditioning and non-air-conditioning between adjacent spaces. The objective is to examine the effect of changing in envelope configurations and HVAC systems' cooling set-points on the overall hygrothermal performance as well as condensation risk on the building envelopes separating the air-conditioned and non-air-conditioned spaces quantitatively.

2 Methodology

2.1 In-Situ Experiments

The study selects a case studied building with a known history of condensation and associated problems including mould growth. The 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. Regarding envelopes, the walls are made of 115 mm bricks finished with 15 - 20 mm rendering on 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 mortar. Additionally, acoustic ceiling tiles of 13 mm thickness are used as ceiling finishes to divide the space into room (3000 mm high) and ceiling plenum (600 mm height) zones. The duct networks for air distribution, located within the ceiling plenum, are well insulated to prevent heat loss and attendant condensation. Equally, the chilled water pipes, wet risers and sprinkler pipes are located within the ceiling plenum.

The ceiling plenum was inspected for possible water leakages during the experiment. The selected air-conditioned space is utilized as academic laboratory while the nonair-conditoned ones are teaching laboratory. In addition, both the air conditioned and non-air conditioned spaces are located in interior zones of the building. Hence, the effects of external weather conditions are considered limited. Both spaces were selected for in-depth study due to higher visible mould growth than other locations in the building. This results presented in this study is part of a series of interdisciplinary research on mould growth in tropical climate building. Interested readers are directed to other companion studies for further information [32, 35-38].

Figure 1 shows a schematic of the case-studied room with the measurement locations. The room on the lower floor is air conditioned where the air is supplied to the room via ceiling mounted supply diffusers. The return system is not ducted hence, air returns to the air handling unit via ceiling plenum. The upper room, on the other hand, is not air-conditioned as the ventilation is mechanical supply and exhaust system. The system brings in the unconditioned outdoor air into the room via ceiling mounted supply and exhaust grilles. During typical operation, the return air from the lower level (inside the ceiling plenum) chills up the upper floor slab and hence lead to condensation on the floor finishes (Figure 1b). A similar occurrence happens to the wall separating the air conditioned, and non-air conditioned spaces where the room is cooled thereby leading to water droplet formation on the corridor-facing side of the wall (Figure 1c). In this study, time-series data of hygrothermal parameters were measured at various locations in the air-conditioned and non-air-conditioned spaces

The data were measured with portable data loggers configured for automated logging at 10 minutes intervals over a period of spanning seven days during the month of May 2014. Measurement positions include supply and exhaust outlets, ceiling plenum, room ambient, and corridor spaces. Further details of the air distribution systems, measuring equipment accuracy and measurement protocols are described in earlier studies by the authors [32, 36, 38].

2.2 Analytical Method for Quantifying Envelope Hygrothermal Quality

Indoor moisture formation depends on the hygrothermal interaction between the building envelopes and the ventilation systems [39]. Moisture moves from high to low vapour pressure regions and as such envelope moisture problems in the temperate climate appear on the warmer interior sides. Contrastingly, in hot and humid climate, the envelopes are prone to moisture formation on
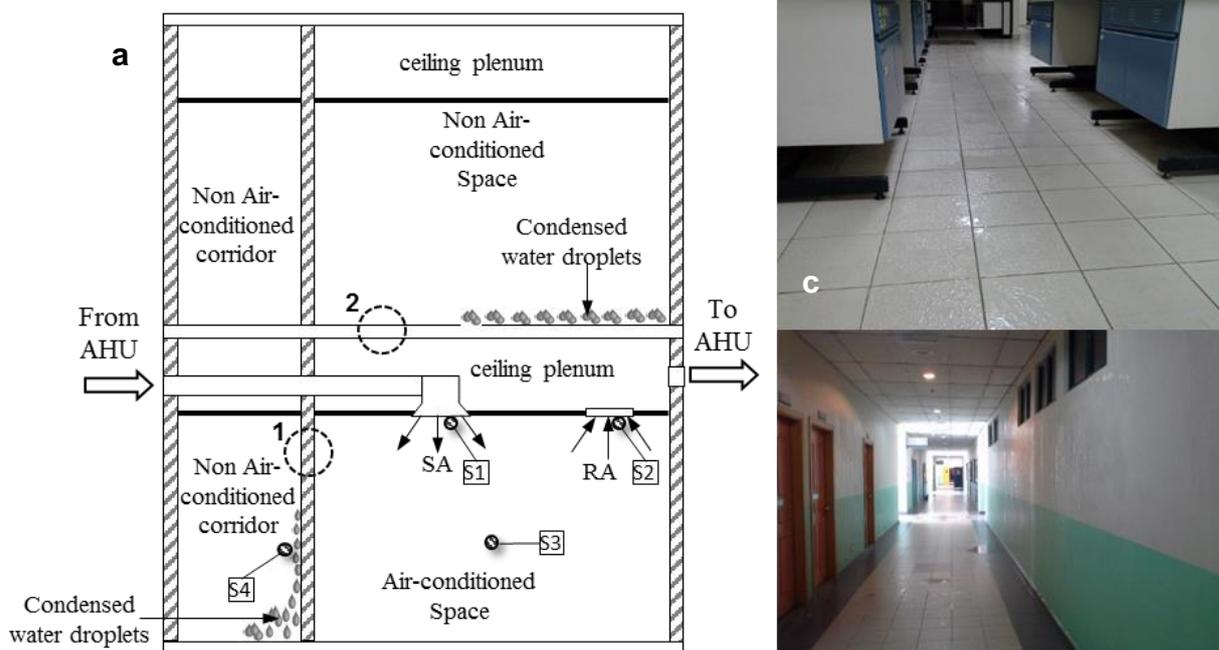

Figure 1. (a) Schematic of vertical cross section through the case-studied room, (b) Condensed water on the floor of non air-conditioned room above air-conditioned room (marked with dashed circle #2 in (a)), (c) condensed water on the wall separating air conditioned space non air-conditioned corridor (marked with dashed circle #1 in (a)) (S1-S4 are T and RH sensors both in the air-conditioned and non-air-conditioned space)

the warmer exterior sides. 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 of envelope hygrothermal quality assessments adapted from the specifications in CIBSE [25] and BSI [13]. A detailed description of the methods and its modifications are as described elsewhere [35].

Using Equations (1) to (7), in-situ hygrothermal data obtained from the time-series measurements were used to calculate the vapour pressure on both conditioned and non-conditioned sides of the envelopes. Values of saturated vapour pressure (p_s), vapour pressure on the cold side (p_c) and vapour pressure on the warm side (p_w) are evaluated from the hourly hygrothermal parameters obtained in the time-series measurements using Equations (1) and (2).

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

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

Subsequently, the study adopts the recommended critical relative humidity (φ_{crit}) of 80% [12, 13, 25]. φ_{crit} is defined as the surface relative humidity that leads to surface deterioration (condensation, corrosion, and mould growth, amongst others). This critical humidity is defined as water activity, a_w in other studies and reports [3, 40].

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

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). Upon calculating the least acceptable saturation pressure, we compute the minimum acceptable surface temperature (θ_{sw}) on the warmer side from Equation (4).

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

The study further defined 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).

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

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

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), 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 relations expressed in equation (7) is used to assess the building hygrothermal quality. A building envelope with lower $fR_{sw,op}$ than or at most equal $fR_{sw,U}$ is of good hygrothermal quality. Similarly, when a building envelope is found in a building which results in higher $fR_{sw,op}$ than $fR_{sw,U}$ then such envelope would invariably be of bad hygrothermal quality. The rating of good or bad quality is related to the ability of an envelope to provide high resistance to moisture and susceptibility to surface condensation. In essence, fR$_{sw,U}$ and fR$_{sw,op}$ are two important variables for controlling condensation and moisture formation on building envelopes.

$$EHQ = \begin{cases} f_{Rsw,op} < f_{Rsw,U}, good\ quality \\ f_{Rsw,op} = f_{Rsw,U}, good\ quality \\ f_{Rsw,op} > f_{Rsw,U}, bad\ quality \end{cases} \qquad (7)$$

where *EHQ* is the envelope hygrothermal quality defined by Equations (5) and (6).

It is imperative to note that while $fR_{sw,U}$ is dependent on envelope overall thermal transmittance, $fR_{sw,op}$ depends on the operative conditions on either side of an envelope. Hence, improvement to mitigate moisture condensation lies mainly on either to improve the envelope overall thermal transmittance or run the air-conditioning systems in a way to provide safe operative conditions. As said earlier, application of this approach had been previously tested and earlier reported [35]. It was found that the envelopes not only failed condensation risk assessment criteria but also found with elevated mould growth risks.

2.3 Assessing Effects of Various Improvements on Envelope Hygrothermal Quality

As the moisture performance of envelope is related to overall thermal transmittance and operative conditions, we tested various insulation improvements and operative conditions on $fR_{sw,U}$ and $fR_{sw,op}$ respectively. To investigate the effects of operative conditions on the envelope performance, we adjust the hourly operative hygrothermal parameters to give average values within the MS 1525 [41] specifications.

Four cases were tested with daily mean operative temperature and relative humidity. To run the tests, we generated random numbers with upper and lower limits representing both thermal and hygric parameters within MS 1525 [41] band – Temperature ranging from 23°C – 26°C and Relative Humidity varying between 55% – 70%. The generated hourly values of temperature and relative humidity were substituted in Equations (1) through (6) to calculate the hourly values of envelope thermal quality due to operative conditions (*fRsw,op*). The daily mean values of operative hygrothermal parameters are considered sufficient for this investigation as the mechanical cooling and ventilation system is of constant air volume (CAV) type.

To quantify the hygrothermal quality due to envelope thermal transmittance *fRsw,U*, we further investigate the effect of various common insulation types and thickness on the envelope quality, *fRsw,U*. The selected insulation types and details of thermal properties of the wall are as presented in Table 1. With each of the selected insulations, the *fRsw,U* were subsequently computed with insulation thickness starting from zero millimetre - representing the existing wall construction without insulation. Subsequent upon the computation with a case of zero insulation, the thickness is varied from 10 mm up to 120 mm. The motivation for our selected thicknesses was as found from earlier studies reported in Magrini [42]. With the assumption that the situation leading to condensation is similar in wall and floor on one hand and the practicability of insulating an existing suspended slab on the other, the procedure described in this study is applied only to the wall. Therefore, the results and discussions are therefore limited to the wall.

Table 1. Thermal properties of the wall with adopted insulation materials

Layer	d (mm)	k (W/mK)
Brickwall		
External surface resistance (Rsw = 0.04 m².K/W)*	-	
External Render	15	0.8
Brick	115	0.77
Internal Plaster	0.015	0.8
External surface resistance (Rsc = 0.13 m².K/W)	-	
Insulation materials		
Mineral wool**		0.036
Fibreboard**		0.040
Polystyrene**		0.033
Polyurethane foam**		0.030

* values obtained from Table 2 of BS EN ISO 13788 [13]
** insulation thickness varies between 0 cm (no insulation) and 12 cm.

3 Results and Discussions

3.1 Hygrothermal Operative Conditions

The results of hygrothermal operative conditions in the case-studied building revealed mean thermal and hygric profiles as: 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 side of the wall (Figure 2). The results hygrothermal conditions show that variations in the field measurements were within the accuracy of the measuring equipment (θ = ± 0.5°C, φ = ±3%) as similarly demonstrated in Oladokun [43]. This proofs that variations in the measured data are due to factors other than the measuring equipment errors. Figure 2 shows a cross section through the existing wall and the operative conditions it is subjected to the air conditioned and nonair-conditioned spaces.
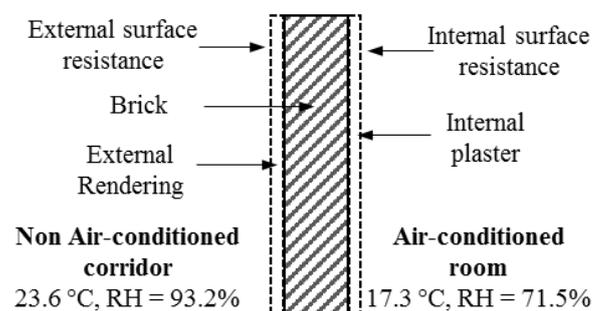

Figure 2. Existing wall section and the mean daily operative conditions on either side of the wall
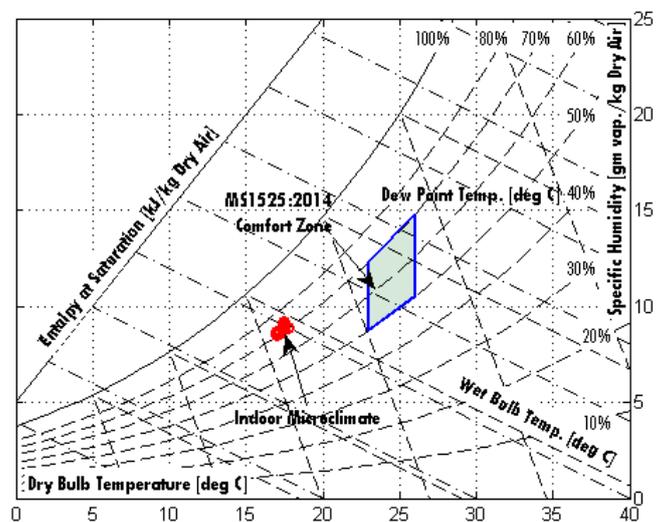

Figure 3. Psychrometric chart showing the average daily operative conditions in the air-conditioned room

Figure 3 shows a plot of the hygrothermal operative conditions on psychrometric charts together with MS 1525 specifications. As revealed in the graph, the hygrothermal operative conditions of the cooling systems were found out of the range specified by MS 1525 [41] where thresholds of temperature (θ) and humidity (φ) are respectively specified as θ = 23 - 26°C and φ = 50 - 70%. The operative conditions revealed an overcooling of the indoor environment – a confirmation that buildings in the hot and humid climates are overcooled [44].

3.2 Envelope Hygrothermal Quality Assessments

Table 2 shows the results of mean values of the computed temperature and relative humidity in compliance with MS 1525 specifications. Again, the computation was done by generating random numbers between the upper and lower boundaries specified by the standard. The results show four test cases in addition to the baseline on-site measured parameters. It should be reiterated that the temperature and humidity of the non-air conditioned side were not optimised and hence remains as the one measured in the test building. Results in Table 2 also shows the values of fRsw,op for the respective temperature and relative humidity. It is revealed that the values of fRsw,op reduced gradually from the baseline value of 1.413 when the operative conditions were θ = 17.3 °C and φ = 71.5% up till -4.965 when the average temperature and humidity improved to 24.3 °C and 61.8% respectively.

Table 2. Average indoor operative conditions and computed Envelope thermal quality due to operative conditions (fRsw,op).

Test Cases	θ_i (°C)	φ_i (%)	*fRsw,op*
Baseline	17.3	71.5	1.413
Test 1	24.3	61.8	-4.965
Test 2	24.8	63.9	-0.553
Test 3	24.6	62.5	0.160
Test 4	24.5	62.8	0.424

Figure 4 shows the graph of *fRsw,U* for the four selected insulation types. From the graph, the horizontal line with values 0.8879 representing the performance value at zero insulation, i.e. the existing wall. As shown in the figure, the highest envelope thermal quality due to thermal transmittance ($fR_{sw,U}$), is obtainable from the use of polyurethane foam insulation, followed by polystyrene insulation. Equally, it is found that the envelope with fiberboard insulation has the least thermal performance. The envelope hygrothermal quality due to overall thermal transmittance performed in a pattern for all the insulations when the thickness is 10 mm. Above this thickness, the performance curve begins to show a near uniform pattern. For instance, the gradient of the curve between 20 mm and 60 mm appears wider than between 60 mm and 100 mm. Although both of the two scenarios have a 40 mm thickness change in insulation, the performance improvements between the former are higher than the later. Hence, that increasing the overall thermal transmittance of a building envelope has a limit at which further improvements give a little gain in the envelope hygrothermal performance.
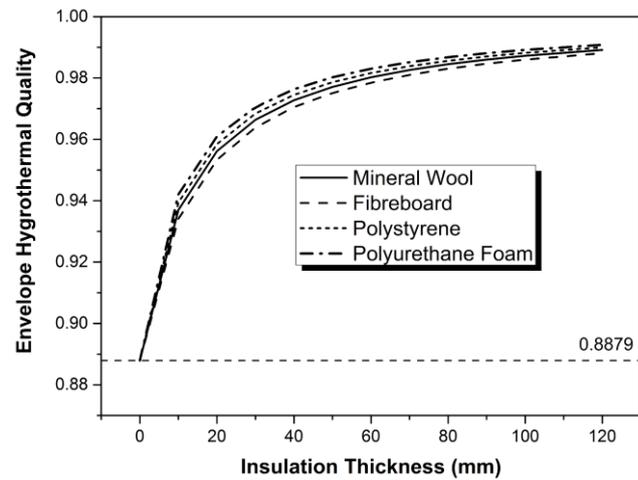

Figure 4. Envelope hygrothermal quality due to overall thermal transmittance for different insulation materials.

For comparison between the envelope hygrothermal quality due to overall thermal transmittance (fRsw,U) and the hygrothermal quality due to operative conditions (fRsw,op), the mean values of fRsw,op is superimposed on the graph of fRsw,U as shown in Figure 5.

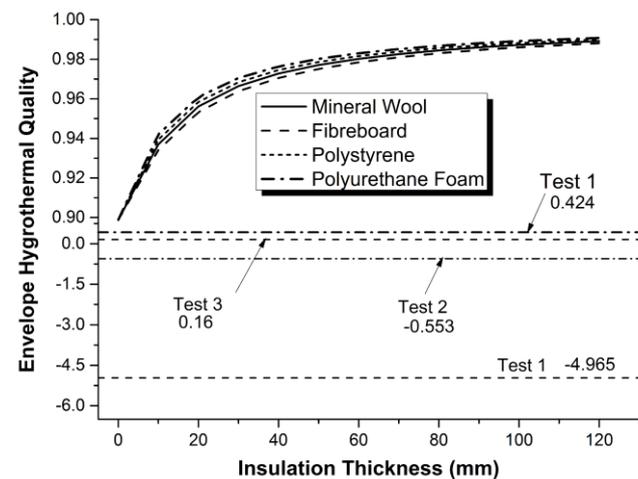**Figure 5.** Comparison between envelope hygrothermal quality *fRsw,U* and *fRsw,op*.

As would be noticed in Figure 4, the curves on the upper part of the graph are similar to that shown in Figure 3. The vertical axis is broken to accommodate both data of *fRsw,U*. and *fRsw,op*. Values represented by the horizontal lines are those of the envelope hygrothermal quality due to operative conditions. It is revealed that for all the computed operative conditions (Test 1 to Test 4), the envelope hygrothermal quality *fRsw,op* falls well below the envelope thermal quality due to overall thermal transmittance *fRsw,U*. As stated earlier, an envelope with fRsw,op less than *fRsw,U* appears of good hygrothermal quality and will provide high resistance to moisture formation. On the contrary, when *fRsw,op* is greater than *fRsw,U* the envelope fails hygrothermal quality assessment and hence would be susceptible to surface condensation.

3.4 Discussions

In this study, the effects of improvements in envelope thermal transmittance and building operative conditions on envelope hygrothermal performance against condensation problems have been investigated with combined field and analytical experiments.

Some further implications of the results and limitations of the study for future investigations are pointed out below. Firstly on insulation improvement for possible moisture condensation control, it is found that increasing insulation thickness may contribute little to moisture control in the tropical climate buildings under differential air-conditioning. The present study is limited to spaces located in the building interior zone with no consideration for external weather influence. Therefore, further studies to include such impact will increase the knowledge in this area. Improved performance is achievable with the control of air-conditioned room operative conditions.

A combination of both insulation options and adjustments in operative conditions would provide additional benefits. Such combinations could be better achieved by building performance simulation tools. Numerical simulations on such combinations are therefore recommended for future studies. Secondly, on the observed improved performance achieved from the modified operative conditions, it is arguable on whether or not the conditions shows in Table 2 for test cases 1 to 4 would make building occupants comfortable. This appears of less concern as, the values are within the MS 1525:2014 specifications. On the contrary, sufficient evidence exists to the various determining factors of thermal comfort. Air movements are of paramount importance in addition to temperature and humidity. Increasing indoor temperature had been observed to be compensated by a corresponding increase in the air movement to improve the comfort of the thermal environment [10].

4 Conclusions

An investigation into the effects of various improvements in the indoor operative conditions and overall thermal transmittance on the hygrothermal quality of building envelopes against condensation risks. A case studied building was selected in the hot and humid climate with differential ventilation between adjacent spaces. The building runs on 24hrs cooling mode in one part against natural on the other. The methodology combined in-situ experiments with a hygrothermal analytical approach that had previously employed for building envelopes thermal quality and condensation risk in the temperate climates. Time-series measurements of hygrothermal parameters were obtained in air-conditioned and non-air-conditioned indoor microenvironments to serve as input in the modified analytical approach. Various insulation types and thicknesses were investigated to the envelope hygrothermal performance. The results of indoor hygrothermal operative conditions revealed that overcooling the air-conditioned side contributes to condensation on the non-air-conditioned side of the envelopes.

The overall thermal transmittance performance upgrade studies revealed envelope failure on surface condensation criteria at existing operative conditions. However, the envelope performed well at improved cooling operative conditions even at existing envelope hygrothermal quality. This further suggest that cooling set-points increase condensation risks on the envelope face abutting the non-air-conditioned spaces in the hot and humid climates. Further enhancements can be achieved by combing cooling operational set-points with envelope overall thermal transmittance improvements. The study provides an essential contribution to the recurring issues of air conditioning and moisture problem in the hot and humid climate of Malaysia. Going forward, as the numerical simulation is proved to be more efficient in building performance diagnosis, further research is recommended in this regards for advanced studies on the effects of each of the contributory factors to moisture problems. Numerical modelling is better in its capability to use validated model for further investigation of various configurations in the test case. Optimisation and further enhancement can then be executed with much confidence. This will further enhance the sustainable operations of facilities in this region thereby creating buildings that are healthier to the users, the envelopes, the stored components and the environment at large through energy efficiency operations.

Acknowledgements

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