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CFD INVESTIGATION OF INDOOR HYGROTHERMAL AND AIRFLOW PROFILE IN ACADEMIC RESEARCH STORAGE ROOM: EFFECT OF LMA ON THERMOHYGRIC BALANCE AND MOULD GROWTH

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ABSTRACT

Ventilation systems maintain thermal comfort and indoor air quality for the building envelopes, occupants and furnishings. The systems often perform in opposite to the design intents despite its high energy outlay. Hence, the need to provide energy efficient buildings without compromising the design purposes had produced various ventilation performance metrics. This study investigates the effect of Local Mean Age (LMA) of air on indoor thermal and hygric balance as well as mould growth. In-situ experiments were combined with computational fluid dynamics (CFD) simulation to assess the indoor hygrothermal and the airflow profile in a mechanically ventilated research store with known history of mould growth. A commercial CFD analysis with the standard k–ε model was used in the CFD simulation. The measurement and validation of the model are reported in a companion paper. The study found that hygrothermal profiles in the stacks depends on airflow field. In most cases, high hygric profile is synonymous with elevated LMA. The poorest locations in LMA shown highest thermohygric balance and visible mould growth on the stored items. The findings suggest that LMA has a significant effect on hygrothermal stratifications as well as indoor mould growth risk.

Keywords: CFD simulation, indoor air quality, local mean age, thermohygric balance, mould growth risk.

INTRODUCTION

Indoor hygrothermal imbalance challenges occupants, stored components and fabrics of such buildings as can lead to elevated moisture, condensation and associated microbial proliferations. Ventilation systems maintain thermal comfort and indoor air quality for the building occupants, envelopes and furnishings. Despite high energy outlay of the systems [1-3], they often result in thermal discomfort and other IAQ issues [4] which, amongst others had hitherto lead to the evolution of building performance diagnostics. Evidence exists in the literature on building ventilation performance diagnosis on thermal comfort and indoor air quality [2, 5], hygrothermal performance and ventilation energy efficiency [6-8]. They are equally focused on design optimisation [9-11] and performance assessment of new building component design [12, 13].

There are various performance metrics for assessing indoor ventilation based on the ventilation system's tasks which are borne out of the need for contaminant removal, air exchange, heat removal and occupant protection [14]. The performance metrics include, but not limited to predicted mean vote (PMV) and predicted percent dissatisfied (PPD) for thermal comfort; local mean age (LMA), air change efficiency (ACE), contaminant removal effectiveness (CRE), local air quality index (LAQI), air diffusion performance index (ADPI), etc. for indoor air quality.

Practical applications of ventilations performance metrics had been previously reported. The suitability of both ACE and CRE formed the focus of a study carried out by Novoselac and Srebric [15] for different indoor spaces, ventilation strategies and contaminant sources. The study revealed that ACE is adapted to the evaluation of ventilation strategies in indoor environments with unknown contamination sources. On the other hand, CRE performs better for removal of contaminants with known position and generation rates. Nevertheless, certain correlation was found between ACE and CRE. Mohammed [16] investigated the effectiveness of displacement ventilation system on thermal comfort and indoor air quality. It was reported that supply velocity affects temperature stratifications with high and low thermal stratifications from low and high supply velocity respectively. In addition, the author establishes a relationship between the local mean age (LMA) of air and the inlet velocity.

The local mean age of air (LMA) is the average period it takes a given volume of supply air to reach any location within the indoor ventilated space [14, 17]. The LMA is useful for assessing the freshness of indoor air. The inlet air is considered to have an age equals zero seconds and as such increased value of LMA indicates the rate of staleness of the air. LMA is related to the airflow and high velocity is usually correlated with low LMA and vice versa. In addition, high airflow results in low

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concentration of contaminants therefore LMA serves as a good indicator of indoor contaminant removal.

In hygrothermal performance assessment, the thermohygric parameters are treated as contaminants and therefore can be investigated with LMA. In an ideal indoor space with high airflow, the rate of air movement over the surfaces is higher, thus maintain the surfaces at equal hygrothermal profile. In essence, high airflow supports higher movement of water molecules, thereby reducing the rate of moisture deposition on the surface. This explains the reason why inadequate ventilation performance can result in an indoor elevated hygric profile and associated mould growth[18]. Such risks are reduced in naturally ventilated buildings in comparison to those ventilated through mechanical means. For instance, Borrego and Perdomo [19] reported in their study that fungal contamination was reduced in naturally ventilated building than the mechanically ventilated ones. The reason, according to the study, is due to the natural ventilation that facilitates the movement of particles in the air thereby making spore deposition difficult.

It is evident from the foregoing that indoor airflow influences the thermohygric balance on one hand and increases chances of mould growth on the other. With the proven ability of LMA as a ventilation performance metric for air freshness, its application to investigating indoor thermohygric balance and mould growth becomes promising in ventilation performance assessments. It is against this background that this study investigates the effect of LMA of air on indoor thermal and hygric balance as well as mould growth in an indoor environment with known cases of microbial proliferations. The aim is to decipher the impact of airflow on the thermohygric fluctuations leading to mould growth so as to increase the understanding of suitable abatement measures. The study combined in-situ experiment with computational fluid dynamics (CFD) simulation.

Although improved microcomputers' computational power has significantly advanced CFD models and research developments in indoor airflow, heat transfer and contaminant transport [20, 21], numerous uncertainties exist in numerical simulations that require suitable clarifications for reliability improvements. Procedures for such suitable uncertainty clarifications on the execution and reporting of numerical simulations are well documented in the body of literatures [22-24]. A companion paper [25] reported the measurement and validation of the model for further investigation in the present study.

NUMERICAL SIMULATION

Model description

The room, measures 5.2 m × 4.8 m × 3.0 m high, is air-conditioned and ventilated by a constant air volume (CAV) air handling unit (AHU) that controls the airflow and hygrothermal distribution within the room. The air distribution system, a mixing type, consists of ceiling mounted four-way supply diffuser and extract grille. The lighting system consists of six numbers ceiling mounted fluorescent fittings (600 mm x 1200 mm) with two numbers 36W lamps. The air outlets as well as light fittings were installed to flush with the ceiling surface. The furniture comprises of metal shelves for keeping stored components in the room. 3D modelling of the experimental room was created within the FLOVENT CFD analysis tool. The walls, floor and ceiling were modelled as adiabatic since the room is bounded with other rooms with similar air-condition. The stored items on the shelves were modelled as rectangular blocks to conserve computational resources.

The items on the shelves are modelled as a row of objects rather than individual items. Since the objects on the shelves allow air movement between them, they were modelled as resistances (porous object) with 20% openings. As the study examines the thermohygric distribution within the shelve and stored components, the simplification is considered sufficient to represent the airflow through the object. A similar approach was adopted in the study reported by Fletcher, *et al.* [26]. One of the many benefits of CFD simulation is the ability to place virtual data loggers at different points of interests other than the in-situ measurement positions. The virtual data loggers allow assessment of the hygrothermal conditions within the shelves and stored items that seems difficult to achieve on site. Figure-1 shows details of the space layouts with positions of supply, exhaust and other components of the case-studied room.

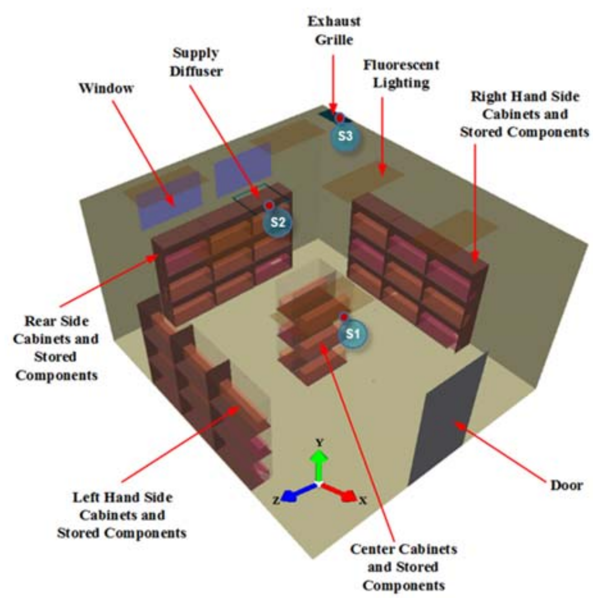

Figure-1. Layouts and positions of supply exhaust and other components of the case studied room.

Governing equations

In the simulation, incompressible steady state Navier-Stokes equation coupled with the standard k–ε turbulence model was employed. Equation. (1) represents the general form of the Navier-Stokes equation [20, 27]. Table-1 presents the dependent variables (ϕ), effective

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diffusion coefficients (Γϕ), and the source term (SΦ) for each of the flow parameters in Equation. (1).

$$\frac{\partial}{\partial t}\left(\rho\ \varphi\right)+div\left(\rho\ V\varphi-\Gamma_{\varphi}grad\,\varphi\right)=S_{\varphi} \quad (1)$$

Where ρ is the density, V is the velocity vector, ϕ is the dependent variable in the flow field to which the equation applies (temperature, velocity, pressure, etc.), Γϕ is the turbulent diffusion coefficient and Sϕ is the source or sink term of the variable ϕ.

Boundary condition, discretisation, grid dependency analysis and model validation

Table-2 presents the basic boundary conditions for the CFD simulation. The discretisation, grid dependency analysis and model validation is reported in the companion paper [28]. The study reported a good correlation between the predicted and measured indoor hygrothermal profile with less than 10% deviation as similar to earlier studies [1, 29, 30] and better than the variation reported by Kavgic, *et al.* [31].

Simulation for airflow and thermohygric profile on the stored items

In this study, extended simulations was carried out on the model. Key parameters were selected for further analysis to predict the hygrothermal and airflow parameters within the shelves and racks of the case studied room. The hygrothermal parameters consist of temperature (T) and relative humidity (RH) while the air speed (s) and local mean age (LMA) chosen for the airflow parameters. The average performance metrics of T, RH, airspeed and LMA were evaluated for the entire occupied zone. In addition, points along the x-axis were selected for contour plots of the parameter profiles. The locations were selected to assess thermohygric distribution as well as airflow profile at: plane before the supply diffuser (0.75 m), a plane that cuts across the supply diffuser (1.5m) and 2.25m for a plane after the supply diffuser.

As further post-processing assessment, the mean LMA in the room is selected as a baseline and plotted on graph of hygrothermal and air flow profiles. The performances of thermohygric and airflow profiles in the stacks are further evaluated.

Table-1. The dependent variables (ϕ), effective diffusion coefficients (Γϕ), and the source term (SΦ) for each of the flow parameters.

Equation	*Φ*	Γ_{Φ}	S_{Φ}
Continuity	1	0	0
x momentum	u	μ	$-\partial P/\partial x$
y momentum (vertical)	v	μ	$-\partial P/\partial y$ - ρg
z momentum	w	μ	$-\partial P/\partial z$
Enthalpy	C_pT	λ	Q
Concentration	c/ρ	d	Q_m
k equation	k	μ/σ_k	$G-\rho\ \varepsilon$
ε equation	ε	μ/σ_ε	$C_1\ \varepsilon\ G/k - C_2\ \rho\ \varepsilon_2/k$
$\mu = \mu_{lam} + \mu_t$ $\mu_t = \rho\ C\mu\ k^2/\varepsilon$ $G = \mu[2[(\partial u/\partial x)^2 + (\partial v/\partial y)^2 + (\partial w/\partial z)^2] + (\partial u/\partial y + \partial v/\partial x)^2 + (\partial v/\partial z + \partial w/\partial y)^2 + (\partial u/\partial z + \partial w/\partial x)^2]$ C1 = 1.44, C2 = 1.92, Cμ = 0.09, σ_H= 0.9, σ_k= 1.0, σ_ε= 1.3			

RESULTS AND DISCUSSIONS

Overall thermohygric and airflow profile

The average performance metrics in the occupied zone were found to be T = 17.2 °C, RH = 78.4%, s = 0.27 m/s and LMA = 149.2 s. Figure-2-4 show the thermohygric and airflow profiles at x = 075m, 1.5m and 2.25m respectively. At x = 0.75m, thermal stratification is revealed in most part of the room. The upper part close to ceiling shows high temperature and low humidity due to heat emission from lighting while concentrated cold region is shown on the air-stream around the supply diffuser (Figure-2a). In addition, regions close to the shelves were found with low thermal and elevated hygric gradients (Figure-2b).

Table-2. Boundary conditions and other settings for CFD simulation.

Items	Details
Room Size	External Dimension: 5.7 x 3.7m x 3.4m high Internal Dimension: 5.4m x 5.1m x 3.3m high
Air Inlet	Air inlet set as inflow Dimension: 600mm x 600mm Supply Temperature = 15.5 °C Humidity Ratio = 9.8 x 10^{-3} kg/kg Airflow rate = 0.61 m^3/s
Air Outlet	Air outlet set as outflow Dimension: 600mm x 300mm Exhaust Temperature and Humidity Ratio are to be computed Exhaust Flow rate = 0.61 m^3/s
Wall	Treated as adiabatic, heat gains from the wall are through the

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	heated panels
Heat Source	Heated Panel on all walls, floor and ceiling surfaces, T = 18 °C, Heat Gain from heated lamps = 6 x 72 W
Wall	Treated as adiabatic, heat gain from the wall is through the heated panels
Grid Details	Size: 10.45 x 5.81 x 9.29 mm Total Number: 9885 Cells Maximum Aspect Ratio: 50.5
Turbulence	Standard *k-ε* model

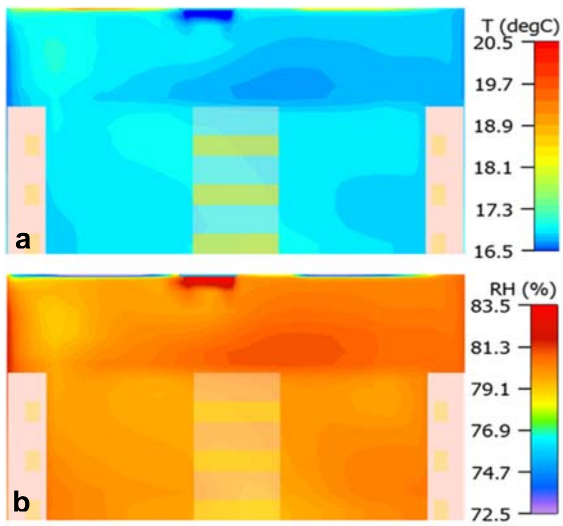

Figure-2. Thermohygric profile at x = 0.75m (a) T contour (b) RH contour.

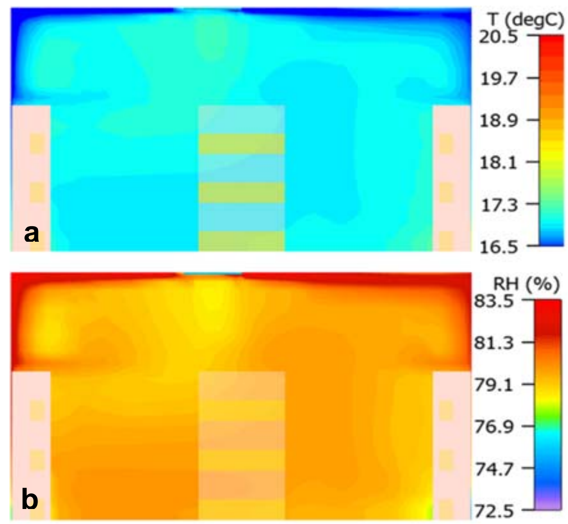

Figure-3. Thermohygric profile at x = 1.5m (a) T contour (b) RH contour.

The hygrothermal profile at x = 1.50m (Figure-3) revealed similar stratifications in the room. Nevertheless, both thermal (Figure-3a) and hygric (Figure-3b) profiles show the airflow throw attached to the ceiling with cold and humid regions near the ceiling. This region continues until the wall where a change of direction and recirculation ensued.Figure-4 shows the thermohygric profile at x = 2.25m with similar thermal and hygric stratifications not only within the room but also around the shelves. These findings suggest that the air in the room is not well distributed.

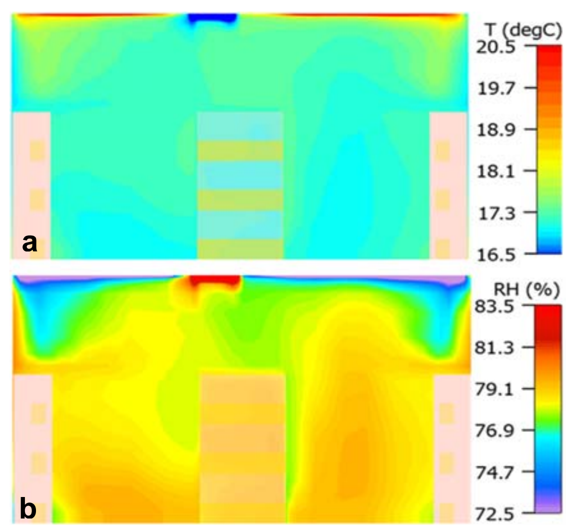

Figure-4. Thermohygric profile at x = 1.5m (a) T contour (b) RH contour.

In a similar pattern to the thermohygric stratifications, the LMA profiles were shown with stratified layers in the room (Figure-5). As LMA measures the rate of freshness of air, the locations with longer LMA appear stale and vice versa. Higher LMA is therefore

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synonymous with high contaminant loadings at such locations. In hygrothermal assessment, the contaminant is mainly the water vapour; hence the risk of higher moisture deposition increases with LMA. Looking at the LMA profile for all the locations, longer LMA characterises the occupied zone as well as the shelf areas which suggest the reasons for higher risk of thermohygric imbalance.

Effect of LMA on thermohygric profile and mould growth

Air staleness and contaminant loading increase with LMA. Since water vapour is considered as contaminant in hygrothermal assessment, high LMA results in higher risk of moist air deposit. Results of further post-processing of simulated results is presented in plots of thermohygric LMA graphs (Figure 6-7).

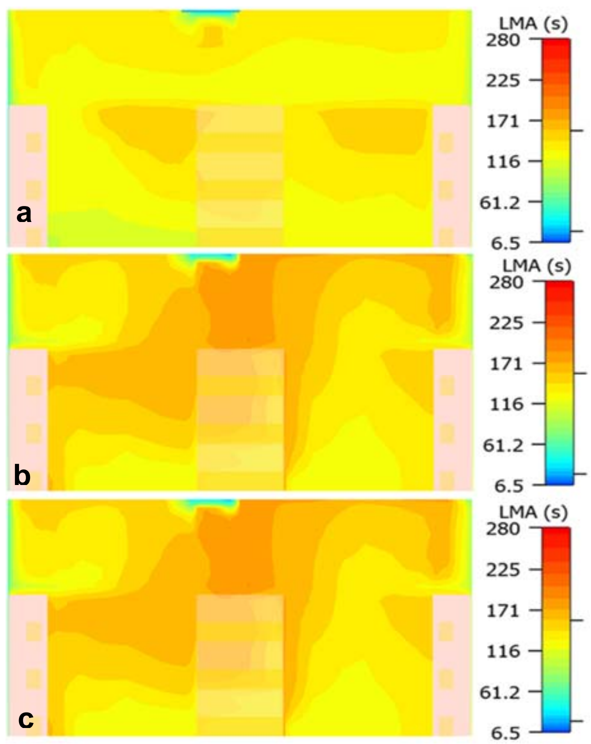

Figure-5. LMA profile at (a) x = 0.75m (b) x = 1.5m and (c) x = 2.25m.

The graphs also include the baseline plot of the mean room LMA value of 149.2 seconds. It is revealed that larger parts of the stacks have their LMA above the benchmark values. Shelve #1 recorded the poorest performance (Figure-6a) with eight out of nine points above 149.2 seconds. This presents shelve #1 as having the highest risk of moisture build-up due to poor air movement. Coincidentally, shelve #1 was found to have highest visible mould growth on the stored components (Figure-6b). This evidenced that elevated LMA results in not only thermohygric imbalance, but also mould growth risk

In addition, shelve #3 recorded the lowest number of points within the stacks with only three out of nine operating at values above the benchmark LMA (Figure-7a). This could be as a result of the shelves closeness to the supply and exhaust openings that facilitate easy air exchange. Shelves #2 have five out of the nine points above the benchmark LMA (Figure-7b), leaving the stack at a lower moisture build-up risk; hence reduced visible mould growth.

Generally, the results of thermohygric and LMA profiles revealed most part of the stacks with flow stratifications. This makes the air to be staler inside the majority of the stacks, a situation that leads to thermohygric stratifications. These stratifications could be primarily due the location of supply and exhaust openings which are located towards one side of the case-studied room. Optimisation could be made in this situation on the best locations for the supply diffuser and exhaust grille that will give a uniform distribution of air within and around the stacks. Such optimisation analysis is beyond the scope of the present studies and therefore recommended for future investigations.

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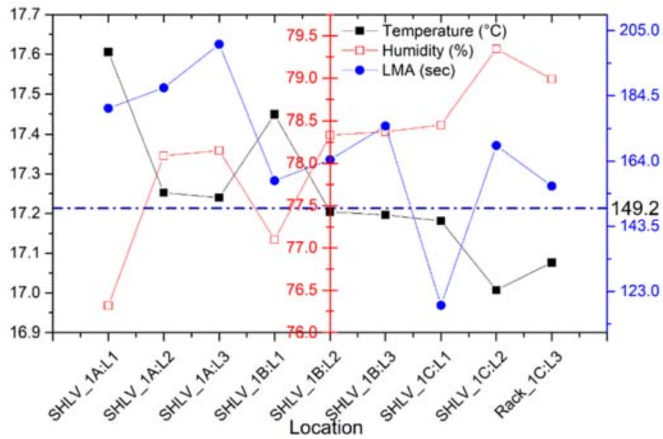
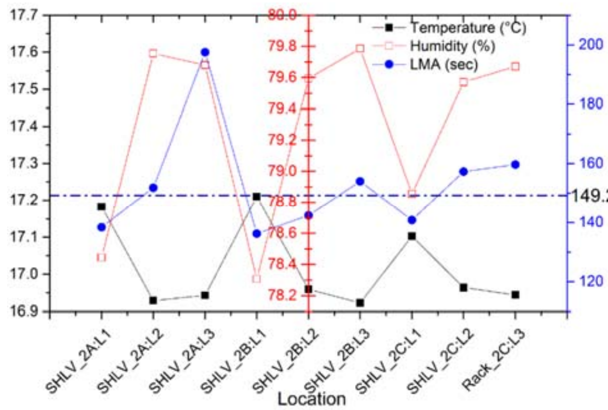


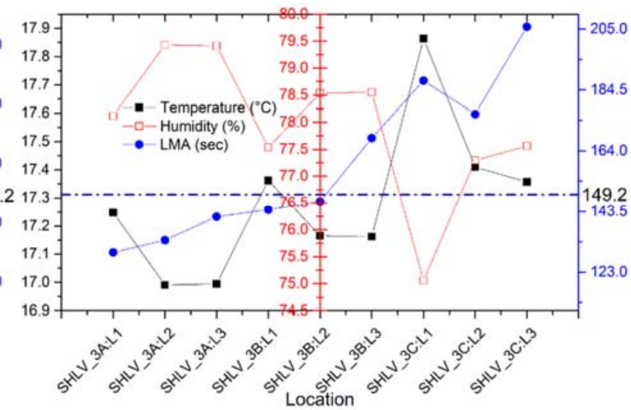
(a)

(b)

Figure-6. (a) Thermohygric and LMA profiles inside shelve #1 (b) Mould growth on stored items inside shelve #1.



(a)



(b)

Figure-7. Thermohygric and LMA profiles inside (a) shelve #2; (b) shelve #3.

CONCLUSIONS

Indoor hygrothermal imbalance challenges occupants, stored components and fabrics of such buildings as can lead to elevated moisture, condensation and associated microbial proliferations. Ventilation systems maintain thermal comfort and indoor air quality for the building occupants, envelopes and furnishings. This study assessed the effect of LMA on indoor thermal and hygric balance as well as mould growth in a mechanically ventilated storage room. In-situ experiment was combined with computational fluid dynamics (CFD) simulation to assess the indoor hygrothermal and airflow profile in a research store with known history of mould growth. A commercial CFD analysis with the standard k–ε model was used in the CFD simulation. The hygrothermal profile within the stacks were shown to be dependent on the airflow field. In most of the stacks, high hygric profile is synonymous with elevated LMA. The poorest stack locations in LMA were found with highest thermohygric imbalance and visible mould growth on stored items. The increase in thermohygric balance and associated mould growth on stacks suggests that LMA has significant effect on hygrothermal stratifications as well as indoor mould growth risk. These stratifications could be primarily due the location of supply and exhaust openings which are located towards one side of the case-studied room.

Optimisation could be made in such situation by varying the size and locations of supply and exhaust outlets, the supply temperature, velocity and airflow rates, etc. then examine the changes on the thermohygric and LMA profiles within and around the stacks. Such optimisation analysis exceeds the scope of the present studies and thus recommended for future explorations.

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