MOULD GROWTH PREDICTION IN TROPICAL CLIMATE BUILDINGS BY USING HYGROTHERMAL DIFFERENTIALS

BY

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ABSTRACT

The rising energy costs, an aftermath of the energy crises of the 1970s, resulted in stringent measures in buildings' design, construction, operation and maintenance. Amongst the several factors of achieving building energy efficiency, airtightness reduces air-conditioning cooling and heating loads. Nevertheless, building airtightness is found to result in problems amongst which are indoor moisture and resultant mould infestation. As the economic development of Malaysia continues, increased numbers of airtight, fully air conditioned buildings are evolving. The high levels of thermal and hygric conditions throughout the year in this environment underscore the role of mechanical ventilation systems in controlling the indoor hygrothermal conditions. The current standard for energy efficiency in Malaysia makes adequate provision for the thermal performance of buildings but gives little considerations for its moisture performance in relation to energy efficiency. Besides, limited guidelines exist for indoor air quality (IAQ) and mould proliferation in Malaysia and the knowledge among the public is lacking. Therefore, a holistic approach is needed for not only the hygrothermal performance but also the associated mould assessment and prediction in these edifices as early detection of the menace is often difficult until growth has advanced. The study combined in-situ, analytical and numerical experiments. The numerical experiments developed computational fluid dynamics (CFD) simulation models and routines for mould growth prediction from the interaction between the building envelopes and hygrothermal differentials of the indoor and outdoor microclimate in mechanically ventilated building. The developed analytical method executed hygrothermal performance assessment of envelopes between air conditioned and non-air conditioned spaces for condensation risk assessment. The results revealed *Penicillium sp.*, *Cladosporium sp.*, *Chaetomium sp.*, *Rhodotorula sp.*, *Fonsecaea sp.*, *Aspergillus sp.* and few other species. The numerical simulation was able to predict the hygrothermal profiles triggering the mould growth. The findings also revealed that the operative cooling set-point of 17.3 °C (temperature) and 71.5% (relative humidity) increases condensation risks on the warm side of the envelopes separating air conditioned and non-air conditioned spaces. The risk is reduced by maintaining the operative cooling set-points in the air-conditioned room at 22 °C to 23 °C. This study provides a holistic approach to designing and retrofitting energy efficient buildings that will be free of microbial infestation due to elevated hygrothermal profiles and increased condensation risk. Equally, this study provides awareness of the effect of differential operations in space air-conditioning on indoor moisture as well as adoptable procedures for mould assessment and predictions in the hot and humid climate of Malaysia. Above all, the study will assist in policy formulation that incorporate hygrothermal performance with energy efficiency.

خلاصة البحث

تكاليف الطاقة في ازدياد مستمر منذ أزمة الطاقة عام 1970م، وذلك نتيجة لاتخاذ التدابير الملحة في المباني، والمتمثلة في: التصميم، والإنشاءات والتشغيل والصيانة. ومن بين العوامل العديدة التي تحقق كفاءة طاقة البناء مقاومةُ تسرب الهواء عن طريق خفض الأحمال للمكيفات المبردة وأجهزة التدفئة، ومع ذلك فقد وجد أنَّ أبنيةَ مقاومةِ تسربِ الهواء تؤدي إلى مشاكل من بينها زيادة نسبة الرطوبة في الأماكن المغلقة، والتي تؤدي بدورها إلى الإصابة بالفطريات أو بالتعفن. ومع استمرار التنمية الاقتصادية الماليزية، فإنَّ وجودَ أعداد متزايدة من أبنية مقاومة تسرب الهواء، وأبنية المكيفات فائقة التطور، والعيش تحت درجات حرارة مرتفعة في هذه البيئة طوال السنة، كلّ ذلك يؤكد على أهمية دور نظم التهوية الميكانيكية من أجل السيطرة على نسبة الرطوبة في الأماكن المغلقة. إنَّ المعيار الحالي لكفاءة الطاقة في ماليزيا يؤدي إلى توفير قدر كافٍ يعمل على زيادة درجة حرارة المباني، ولكنه يعطي قدراً قليلاً من الاعتبارات التي تؤدي إلى زيادة نسبة الرطوبة المرتبطة بنسبة كفاءة الطاقة. وإلى جانب ذلك كله فإنَّنا نفتقر إلى وجود المبادئ التوجيهية التي تؤدي إلى الحصول على جودة الهواء في الأماكن المغلقة (IAQ)، مع انتشار نسبة العفونة في ماليزيا. لذا فإنَّ هناك حاجةً ملحةً إلى منهج شامل ليس فقط لقياس نسبة الرطوبة الحرارية، بل في الوقت ذاته لتقييم العفونة المرتبطة بتلك الرطوبة، ومحاولة التنبؤ في هذا الصدد بما يعرف بالكشف المبكر عن هذا الخطر، وهو أمر يكون الكشف عنه غالباً في غاية الصعوبة قبل مراحل النمو الأخيرة. ولقد جمعت هذه الدراسة بين الجانبين التحليلي والتجارب الرقمية الإحصائية. إنَّ تقنيات التحليل العددي الديناميكي (CFD) عبارة عن نماذج تشبيهية أو محاكية وإجراءات روتينية منتظمة للتنبؤ بنمو العفن أو الفطريات عن طريق التفاعل بين بناء أبنية التهوية والفروق في نسبة الرطوبة الحرارية للمناخ الداخلي والخارجي في أبنية التهوية الميكانيكية. وقد تم تنفيذ منهج تحليلي متطور لرصد المساحات مكيفة الهواء والمساحات غير المكيفة؛ لتخمين مخاطر التكثيف. وقد كشفت النتائج عن وجود مساحات مصابة بالفطريات النباتية، ومساحات مصابة بالفطريات الأسرية، ومساحات للخمائر المتوردة، ومساحات مصابة بالفطريات الأسرية الاستوائية، ومساحات لفطريات نقص المناعة الرشاشية، ومساحات لبعضٍ من أنواع الفطريات الأخرى. وكانت تلك المحاكاة قادرة على التنبؤ بحدوث الرطوبة الحرارية التي تؤدي إلى نمو الفطريات العفنة. وقد كشفت النتائج أيضاً أنَّ عامل التبريد حصل على درجة حرارة مقدارها 17.3 °C ونسبة رطوبة مقدارها 71.5 °C بالإضافة إلى مخاطر الكثافة، وبالمثل فإنَّ هذه الدراسة أشارت إلى أهمية الوعي بتأثير العمليات التفاضلية في المساحاتِ مكيفةِ الهواء على الرطوبة في الأماكن المغلقة، وكذلك إجراءات تقييم نسبة التعفن، وذلك في البيئة التي تتسم بالمناخ الحار والرطب في ماليزيا، وإضافة إلى كل هذا فإنَّ هذه الدراسة تسهم في صياغة السياسات التي تتضمن الربط بين نسبة الرطوبة الحرارية وكفاءة استخدام الطاقة.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Science in Building Services Engineering.

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DECLARATION

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To the memory of my late mother, who taught me to be self-reliant while having trust and faith in Allah.

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LIST OF ABBREVIATIONS

2D	Two-Dimensional
3D	Three-Dimensional
4D	Four-Dimensional
AAS	Active Air Sampling
ACE	Air Change Efficiency
ACH	Air Change per Hour
ACMV	Air Conditioning and Mechanical Ventilation Systems
ADPI	Air Diffusion Performance Index
AHU	Air Handling Unit
AIHA	American Industrial Hygiene Association
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BES	Building Energy Simulation
BRE	Building Research Establishment
BRI	Building Related Illness
BSEEP	Building Sector Energy Efficiency Project
BSI	British Standards Institution
CAD	Computer Aided Design
CAV	Constant Air Volume
CFD	Computational Fluid Dynamics
CFU	Colony Forming Unit per cubic meters of air
CI	Confidence Interval
CIBSE	Chartered Institute of Building Services Engineering
CRE	Contaminant Removal Effectiveness
DBT	Dry Bulb Temperature
DOE	Department of Environment
DOSH	Department of Occupational Safety and Health
DPT	Dew Point Temperature
DTM	Dynamic Thermal Modelling
GBI	Green Building Index
GDP	Gross Domestic Product
HAM	Heat Air and Moisture

HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IBPS	Integrated Building Performance Simulation (IBPS)
ICOP	Industrial Code of Practice
IEQ	Indoor Environmental Quality
IIBF	IIUM Institute of Islamic Banking & Finance
IIUM	International Islamic University Malaysia
IRT	Infrared Thermography
ISO	International Organization for Standardization
ISTAC	International Institute of Islamic Thought and Civilisation
KOM	Kulliyyah of Medicine
LAQI	Local Air Quality Index
LED	Light Emitting Diode
LMA	Local Mean Age
LOC	Level of Confidence
MRSA	Mycobacterium Tuberculosis, Methicillin Resistant Staphylococcus Aureus
MS	Malaysia Standards
MSEF	Mechanical Supply and Exhaust Fan
MVOC	Microbial Volatile Organic Compound
NRE	Ministry of Natural Resources & Environment
PAS	Passive Air Sampling
PCA	Principal Component Analysis
PDA	Potato Dextrose Agar
PMV	Predicted Mean Vote
POI	Point of Interest
PPD	Predicted Percent Dissatisfied
PRMSD	Percentage of Root-Mean Square Deviation
RH	Relative Humidity
SBS	Sick Building Syndrome
SDA	Sabouraud Dextrose Agar
T	Temperature
TOW	Time of Wetness
WBT	Wet Bulb Temperature
WHO	World Health Organisation

LIST OF SYMBOLS

a_w	Water Activity on the material surface
C_I	Concentration as the number of colony forming units of indoor air (cfu/m^3)
C_m	Measured Parameter
C_s	Simulated Parameters
m	Mould Growth Index
n	Number of hourly data observations
N	Number of points under considerations
n_{cfu}	Total number of colony forming units on the agar plates
Δp	Vapour Pressure Excess/Moisture Balance (Pa)
p	Pressure (Pa)
p_a	Atmospheric Pressure of moist air (Pa)
p_c	Air Vapour Pressure for cold air-conditioned side (Pa)
p_i	Partial Vapour Pressure of air (Pa)
p_s	Saturated Vapour Pressure (Pa)
$p_s(\theta_{sw})$	Saturated Vapour Pressure at minimum surface temperature (warm side) to prevent condensation (Pa),
p_{si}	Saturated Vapour Pressure (Pa)
p_w	Air Vapour Pressure for warm non-air-conditioned side (Pa)
R_{sc}	Surface Heat Transfer Coefficient on the cold air-conditioned side (m^2.K/W)
R_{sw}	Surface Heat Transfer Coefficient on the warm non- air-conditioned side (m^2.K/W)
SE_M	Standard Error of Mean
Sϕ	Source or Sink term of variable ϕ
t	Time (s)
U	Envelope thermal transmittance (W/m^2.K)
u	x-velocity (m/s)
V	Velocity Vector
v	y-velocity (m/s)
V_I	Total sampling volume (m^3)
w	z-velocity (m/s)
x_s	Air Moisture Content at saturation (g_w/kg_a)

x_v	Air Moisture Content at ambient (g_w/kg_a)
z	z-value
$\Gamma\phi$	Turbulent Diffusion Coefficient
ε	Contaminant Removal Effectiveness
ε_a	Air Exchange Efficiency
θ	Measured Temperature (°C)
θ_{sw}	Minimum Surface Temperature (warm side) to prevent condensation (°C)
ρ	Material Density (kg/m^3)
σ	Standard Deviation
ϕ	Dependent Variable in the flow field
φ	Measured Relative Humidity (%)
φ_{crit}	Critical Relative Humidity (%)

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

The need to preserve fossil fuel and reduction in carbon footprint result in energy efficient schemes in the 21st century (Di Giuseppe, 2013). This gave rise to better insulated and airtight building envelopes (Künzel and Holm, 2009; Di Giuseppe, 2013). Building insulation and airtightness on the contrary, resulted in moisture and dampness related problems (Adan and Samson, 2011). The sensitivity of such buildings to moisture problems is very high in comparison to the traditional, poorly insulated ones (Künzel and Holm, 2009).

Building interior is expected to provide a safe haven for its occupants. It is expected to shield them from the harsh environmental conditions of excessive temperature, high humidity, particulates and other suspended pollutants. Nevertheless, the case is on the contrary as buildings are found to impact its occupant's well-being (American Industrial Hygiene Association, n.d.; New York City Department of Health and Mental Hygiene, n.d.). Amongst the contributing factors to the impacts of buildings is microbial proliferation (Mahooti-Brooks, Storey, Yang, Simcox, Turner and Hodgson, 2004).

Microorganisms form layers of biofilms on building surfaces (Di Giuseppe, 2013; American Industrial Hygiene Association, n.d.). Bio-deterioration, facade defacement and above all, Sick Building Syndrome (SBS) or other Building Related Illness (BRI) are some of the resultant effects. Superbugs are found to be responsible for nosocomial, the Hospital Acquired Infections (Cruez, n.d.). Cases of occurrence in some Malaysia's public hospitals were reported by New Straits Times in 2004 and 2008 respectively (Cruez, n.d.). *Mycobacterium Tuberculosis*, *Methicillin Resistant Staphylococcus Aureus* (MRSA), *Staphlylococci, Pseudomonads*, *Enterococci* and *E.coli* are the identified nosocomial causing species. The menace of superbugs has been reported as an international problem that has become serious concern to the health practitioners in terms of loss of human life and financial mishap. About 5,000 patients die of MRSA annually in the United Kingdom while the United States, an increase in the death case was reported with 11,000 and 17,000 cases of MRSA related death in 1999 and 2005 respectively (Cruez, n.d.).

There had been an association between moisture-ladened indoor environment and incidence and pervasiveness of Building Related Illness (Robbins, Swenson, Nealley, Kelman and Gots, 2000; Elena and Douglas, 2001; Frederick and William, 2003). Dampness in house encourages the growth of microbiological organisms which increases the adverse effect risks on occupants' health, degradation of building material, loss of aesthetics of building finishes and above all results into a decline in the indoor air quality (IAQ) (Di Giuseppe, 2013).

Consequently, there is the need for environmentally responsive design and assessment approaches that will serve to mitigate against committing reliance errors on energy efficient technologies which are often associated with the 'business as usual' buildings (University of Cambridge, n.d.).

1.2 PROBLEM STATEMENTS

The energy crises of the 1970s has resulted in energy efficiency measures. Consequently, the energy efficiency has given rise to air-tight buildings. This is because infiltration and ex-filtration of outdoor and indoor air give rise to high heating and/or