Enhancing Thermal Comfort in a Room Using Natural Ventilation, Phase Change Materials and Green Wall Biofilters

By

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Certificate of Original Authorship

I, Peter Abdo declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Mechanical and Mechatronic Engineering / Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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List of publications

Following is a list of journal articles, peer reviewed conference proceedings and reports associated with my PhD research study:

Journal articles

1. **Abdo, P.**, Taghipour, R. & Huynh, B. P. (2019). Three Dimensional Simulation of Wind Driven Ventilation through a Windcatcher with Different Inlet Designs, *ASME Journal of Thermal Science and Engineering Applications*. **(Revision Under review)**
2. **Abdo, P.**, Huynh, B. P., Irga, P. J., & Torpy, F. R. (2019). Evaluation of air flow through an active green wall biofilter. *Urban Forestry and Urban Greening*, *41*, 75-84. doi:10.1016/j.ufug.2019.03.013
3. Pettit, T., Irga, P. J., **Abdo, P.**, & Torpy, F. R. (2017). Do the plants in functional green walls contribute to their ability to filter particulate matter?. *Building and Environment*, *125*, 299-307. doi:10.1016/j.buildenv.2017.09.004
4. Irga, P. J., Paull, N. J., **Abdo, P.**, & Torpy, F. R. (2017). An assessment of the atmospheric particle removal efficiency of an in room botanical biofilter system. *BUILDING AND ENVIRONMENT*, *115*, 281-290. doi:10.1016/j.buildenv.2017.01.035
5. Irga, P. J., **Abdo, P.**, Zavattaro, M., & Torpy, F. R. (2017). An assessment of the potential fungal bioaerosol production from an active living wall. *BUILDING AND ENVIRONMENT*, *111*, 140-146. doi:10.1016/j.buildenv.2016.11.004

Peer Reviewed Conference Proceedings

6. **Abdo, P.**, Huynh, B. P., Braytee A., & Taghipour, R. (2019). EFFECT OF PHASE CHANGE MATERIAL ON TEMPERATURE IN A ROOM FITTED WITH A WINDCATCHER. In *Proceedings of the ASME 2019 International Mechanical Engineering Congress and Exposition (IMECE2019)*. Salt Lake City, UT, USA: The American Society of Mechanical Engineers (ASME).

7. **Abdo, P.**, Taghipour, R., & Huynh, B. P. (2019). THREE DIMENSIONAL SIMULATION OF THE EFFECT OF WINDCATCHER`S INLET SHAPE. In *Proceedings of the ASME - JSME - KSME Joint Fluids Engineering Conference 2019*. San Francisco, CA, USA
8. **Abdo, P.**, Taghipour, R., & Huynh, B. P. (2019). THREE DIMENSIONAL SIMULATION OF VENTILATION FLOW THROUGH A SOLAR WINDCATCHER. In *Proceedings of the ASME - JSME - KSME Joint Fluids Engineering Conference 2019*. San Francisco, CA, USA.
9. **Abdo, P.**, Taghipour, R., & Huynh, B. P. (2018). Simulation of Buoyancy Driven and Winddriven Ventilation Flow in a Three Dimensional Room Fitted with a Windcatcher. In T. C. W. Lau, & R. M. Kelso (Eds.), *Proceedings of the 21st Australasian Fluid Mechanics Conference*. Adelaide, Australia: The Australasian Fluid Mechanics Society.
10. **Abdo, P.**, Huynh, B. P., & Avakian, V. (2018). EFFECT OF GREEN WALL MODULES ON AIR TEMPERATURE AND HUMIDITY. In *Proceedings of the ASME 2018 5th Joint US-European Fluids Engineering Division Summer Meeting (FEDSM2018)*. Montreal, Quebec, Canada: The American Society of Mechanical Engineers (ASME). doi:10.1115/FEDSM2018-83139
11. Taghipour, R., **Abdo, P.**, & Huynh, B. P. (2018). Effect of Wind Speed on Ventilation Flow Through a Two Dimensional Room Fitted With a Windcatcher. In *Proceedings of the ASME 2018 International Mechanical Engineering Congress and Exposition (IMECE2018)*. Pittsburgh, PA, USA: The American Society of Mechanical Engineers (ASME). doi:10.1115/imece2018-88666
12. **Abdo, P.**, Taghipour, R., & Huynh, B. P. (2018). EFFECT OF WINDCATCHER'S INLET SHAPE ON VENTILATION FLOW THROUGH A TWO DIMENSIONAL ROOM. In *Proceedings of the ASME 2018 5th Joint US-European Fluids Engineering Division Summer Meeting (FEDSM2018)*. Montreal, Quebec, Canada: The American Society of Mechanical Engineers (ASME). doi:10.1115/FEDSM2018-83141
13. **Abdo, P.**, Huynh, B. P., & Avakian, V. (2018). Effect of Fan Speed on Air Flow through a Green Wall Module. In *Proceedings of the ASME 2018 5th Joint US-European Fluids Engineering Division Summer Meeting (FEDSM2018)*. Montreal, Quebec, Canada: The American Society of Mechanical Engineers (ASME). doi:10.1115/FEDSM2018-83199
14. **Abdo, P.**, & Huynh, B. P. (2018). Effect of passive green wall modules on air temperature and humidity. In *ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE)* Vol. 7. Pittsburgh, Pennsylvania. doi:10.1115/IMECE2018-86963

15. **Abdo, P.**, Huynh, B. P., & Avakian, V. (2017). Distribution of Air Flow through a Green Wall Module. In *ASME 2017 Fluids Engineering Division Summer Meeting* Vol. 1B. Waikoloa, Hawaii, USA. doi:10.1115/FEDSM2017-69134
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17. **Abdo, P.**, Huynh, B. P., Avakian, V., Nguyen, T. T., Gammon, J., Torpy, F. R., & Irga, P. J. (2016). Measurement of air flow through a green-wall module. In *Proceedings of the 20th Australasian Fluid Mechanics Conference*. Perth: Australasian Fluid Mechanics Society.

Reports

18. Irga, P. J., Paull, N. J., **Abdo, P.**, Huynh, B. P., Avakian, V., Nguyen, T., & Torpy, F. (2017). *DEVELOPING THE JUNGLEFY BREATHING WALL FOR ENHANCED INDOOR AIR QUALITY REMEDIATION*. Sydney, Australia.
19. Pettit, T., Irga, P., **Abdo, P.**, Huynh, B., Stephen, J., & Torpy, F. R. (2017). *DEVELOPMENT AND AUGMENTATION THE JUNGLEFY BREATHING WALL*. Sydney, Australia: UTS.

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Nomenclature

Symbols

C_1, C_2, σ_k,and σ_ε : Realisable K-ε model constants, dimensionless

C_p: Air specific heat [J/(kg K)]

K: Turbulent kinetic energy [m^2/s^2]

k: Air thermal conductivity [W/(m K)]

L: Characteristic length [m]

T: Temperature [K]

T_o: Reference Temperature [K]

Pr_t: Turbulent Prandtl number

κ: Von Karman constant [dimensionless]

ε: Dissipation rate of turbulent kinetic energy [m^2/s^3]

ρ: Air density [kg/m^3]

μ: Air dynamic viscosity [Pa s]

υ: Air kinematic viscosity [m^2/s]

β: Thermal expansion coefficient [1/K]

A: Area [m^2]

B: A constant

C: A constant

D: Diameter [m]

K: Loss coefficient

P: Gauge pressure reading [Pa]

Q: Air flow rate [L/s or m^3/s]

Subscripts

F-L: Funnels, large

F-S: Funnels, small

Free: No funnels used; the module is free

Dry: Dry condition

Wet: Wet (saturated) condition

S: Plant-growing medium (Soil replacement)

Acronyms

ADC: Analogue to Digital Convertor

CFD: Computational Fluid Dynamics

DNS: Direct Numerical Simulation

FVM: Finite Volume Method

GUI: Graphical User Interface

HVAC: Heating, Ventilation and Air Conditioning

IAQ: Indoor Air Quality

LES: Large Eddy Simulation

LWS: Living Wall Systems

MUX: Multiplexer

PCM: Phase Change Material

PM: Particulate Matter

RANS: Reynolds Averaged Navier-Stokes

RNG: Re-Normalisation Group

SBS: Sick Building Syndrome

VOCs: Volatile Organic Compounds

Abstract

Natural ventilation is the process of supplying and removing air through an indoor space by natural means. There are two types of natural ventilation occurring in buildings: wind-driven ventilation and buoyancy-driven ventilation. Efficient design for natural ventilation in buildings should implement both types of ventilation. Furthermore the architectural design of the windcatcher inlet affects its performance and influences the occupant's human comfort. Combining the wind-driven and the buoyancy-driven ventilation will be investigated in this study using a windcatcher natural ventilation system. The effect of the windcatcher's inlet design is also investigated to achieve better air flow and to increase the efficiency of windcatchers. Experimental studies of windcatcher systems are very costly and mostly impossible in practice. CFD (computational fluid dynamics) tools will be used in this research to simulate the air flow through a two sided windcatcher. Two dimensional and three dimensional simulations are performed using Ansys Fluent and CFD Ace + to obtain quantitative and qualitative analysis of velocity magnitude, flow patterns and ventilation flow rate.

Furthermore, the increased pollution levels in cities highlights the importance of innovative strategies that can help to improve the quality of air introduced into buildings.

Green walls have recently been used to help with this and even thermal comfort. Enhancing the flow distribution and air flow rate through active green wall modules will be studied in this research considering the different parameters involved such as module geometry, moisture content, growing-medium-plant-roots mix and plant type. The current work represents a detailed assessment of airflow through an active green wall module. Airflow distribution through the module, the effect of wetting the substrate, and the effect of introducing a cover to the module's open top face were investigated, with the aim to improve the module's design and achieve more appropriate and effective airflow. Four cases of both planted and unplanted modules under both dry and wet conditions are considered. This work's primary observation is that ***more*** air will pass through a typical green wall substrate, and hence become cleansed, when the substrate is saturated wet more than when it is dry. The increase was substantial at approximately 50% more with 14.9 L/s total air flow rate passing through the wet planted module versus 10 L/s when dry. Reducing the 15.5 % of airflow passing through the module's open top face was found to be essential to maximize the bio-filtration capacity. Adding a top

cover to the module having six 10 mm holes for irrigation decreased the airflow through the top by 6 %, and directed it through the filter increasing the percentage of air flow passing through the front openings from 79 % to 85 %.

The effect of green walls on thermal comfort (Temperature and humidity) is also experimentally investigated. For the active modules, lower temperatures in the range of 1 to 3 °C, along with increased humidity levels have been observed when modules are saturated wet, similarly passive modules provided lower temperatures in the range of 0.5 to 2 °C. None of the plant species studied showed any preference, indicating that the moisture content of the substrate plays the major role affecting the temperature and humidity variations.

The effect of using phase change material (PCM) as a passive cooling technique on the performance of a windcatcher to meet the demand for thermal comfort, hence energy conservation and savings purposes, is studied in this research. Incorporating PCM located in the floor, ceiling and walls of a room as well as in the windcatcher's inlet channel has shown the best performance. This set up provided a significant reduction of temperatures during the discharging process of about 3.61 ºC (equivalent to 9.33%) and an increase in the average temperatures of 3.40 ºC (equivalent to 15.70 %) during the charging process (solidification of PCM) compared with an empty room with no PCM. The effect of PCM on humidity was not significant as variations of maximum 3.88% is observed when PCM is used.

The ultimate aim of this research is to develop a natural ventilating system to enhance a healthy, comfortable and energy efficient indoor environment; PCMs and green wall modules are appropriately incorporated.