EFFECT OF VENTILATION FAN ON THERMAL COMFORT IN A MEDIUM SIZE MOSQUE

FAWAZ AHMED GHALEB

UNIVERSITI TEKNOLOGI MALAYSIA

EFFECT OF VENTILATION FAN ON THERMAL COMFORT IN A MEDIUM SIZE MOSQUE

FAWAZ AHMED GHALEB

A thesis submitted in fulfilment of the requirements for the award of the degree of Doctor of Philosophy (Mechanical Engineering)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

OCTOBER 2017

To my beloved parents,

My amazing wife and our children

My kind sisters and brothers

And not forgetting to all my friends

For their

Sacrifice, Love, and Encouragement

ACKNOWLEDGEMENT

Firstly, all my praise and thanks are owed to Allah, who honoured me the health and persistence who substantially depends on Him.

I would like to express my sincere gratitude and appreciation to my main supervisor, Associate professor Dr. Haslinda Mohamed Kamar. Her guidance, care, time, attention and assistance had been the key to the arrival to this destination. I am also grateful to my co-supervisor, Associate professor Dr. Nazri Kamsah. I wish to express my sincere appreciation to him for all his kind guidance and inspiration to make this research possible. His personality, enthusiasm, patience and intellectual spirit made him a great supervisor and invaluable role model for my professional career.

In addition, I am extremely grateful to the Ministry of Higher Education the Republic of Yemen represented by Aden University for their full support and sponsoring during my study. I would like to thank all the staff at Faculty of Mechanical Engineering, Universiti Teknologi Malaysia (UTM) for providing the resources, facilities and instruments required for this research.

Finally, I sincerely express my thanks to my family and friends for their assistance and patience throughout the study. Unfortunately, it is not possible to list all of them in this limited space.

ABSTRACT

A mosque is a place for the Muslims to perform their congregational prayers and other communal religious activities in Malaysia and other Islamic countries. Most of the mosques in Malaysia are not thermally comfortable. Thermal comfort inside a confined space is essential for health, well-being as well as productivity. A traditional method to provide thermal comfort inside the Malaysian mosque is by using natural ventilation and wall, ceiling and stand fans. However, this method is not capable of providing adequate thermal comfort due to low average wind velocity, and limitation of the fans to displace the warm air. The goal of this study is to identify ways to improve thermal comfort in a chosen mosque located in Johor Bahru. Field measurements were first carried out to determine the airflow velocity, temperature, humidity and mean radiant temperature inside the mosque. The measurements were performed from 11 a.m. to 3 p.m., in the middle of each month, for a one-year duration. Thermal comfort inside the mosque was determined by evaluating the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) indices. The findings showed that the PMV and PPD indices inside the mosque are outside the comfort range stipulated in the ASHRAE Standard-55. A computational fluid dynamics (CFD) method was employed to predict the distribution of airflow velocity, humidity, and air temperature inside the mosque. The CFD models were validated based on the measured airflow velocity, humidity, and air temperature. A grid independent test (GIT) was done to reduce the effects of meshing on the results while grid convergence index (GCI) was carried out to estimate the discretization error. A parametric analysis was carried out to identify a suitable number of exhaust fans and their placements that would give the greatest improvement on both the PMV and PPD values. The results showed that by placing ten exhaust fans with 1-meter diameter on the south-side wall of the prayer hall produces a more uniform airflow distribution, increases airflow velocity by 84% and decreases air temperature and humidity by 16% and 6.3%, respectively. In addition, the PMV and PPD improved by 78% and 90%, respectively. This study has shown that a proper selection of the number and placement of exhaust fans could improve thermal comfort in a large confined space.

.

ABSTRAK

Masjid adalah tempat bagi umat Islam melaksanakan solat jemaah dan aktiviti keagamaan di Malaysia dan negara Islam yang lain. Kebanyakan masjid di Malaysia adalah tidak selesa secara terma. Keselesaan terma di dalam sesebuah ruang tertutup penting untuk kesihatan, kesejahteraan juga produktiviti. Kaedah tradisional menyediakan keselesaan terma di dalam masjid di Malaysia adalah dengan menggunakan pengudaraan semula jadi dan pelbagai jenis kipas. Namun begitu, kaedah ini tidak mampu memberikan keselesaan terma yang mencukupi kerana purata halaju angin yang rendah, dan ketidakmampuan kipas untuk menyingkirkan udara panas. Matlamat kajian ini adalah untuk mengenal pasti kaedah bagi menambah baik keselesaan terma di dalam masjid yang terpilih di Johor Bahru. Pengukuran di lapangan bagi menentukan halaju udara, suhu udara, kelembapan udara dan suhu permukaan dinding dilakukan di dalam masjid. Pengukuran dijalankan dari pukul 11.00 pagi hingga 3.00 petang, pada pertengahan setiap bulan, untuk tempoh satu tahun. Keselesaan terma di dalam masjid ditentukan dengan menilai Ramalan Vot Min (PMV) dan Peratusan Ramalan Ketidakpuasan (PPD). Penemuan kajian menunjukkan bahawa indeks PMV dan PPD di dalam masjid berada di luar julat keselesaan yang ditetapkan oleh ASHRAE Standard-55. Kaedah dinamik bendalir pengkomputeran (CFD) digunakan untuk meramal taburan halaju udara, kelembapan udara, dan suhu udara di dalam masjid. Model CFD disahkan berdasarkan data halaju udara, kelembapan udara, dan suhu udara yang diukur. Ujian bebas grid (GIT) dilakukan untuk mengurangkan kesan grid ke atas keputusan manakala indeks penumpuan kekisi (GCI) dilakukan untuk menganggarkan ralat pengdiskretan. Analisis parametrik dilakukan untuk mengenal pasti bilangan kipas ekzos yang sesuai dan lokasinya yang akan memberi nilai PMV dan PPD yang lebih baik. Dapatan kajian menunjukkan bahawa dengan meletakkan sepuluh kipas ekzos dengan garis pusat 1-meter di dinding sebelah selatan dewan utama menghasilkan taburan halaju udara yang lebih seragam, meningkatkan kelajuan aliran udara sebanyak 84% dan masing-masing menurunkan suhu udara dan kelembapan udara sebanyak 16% dan 6.3%. Di samping itu, meningkatkan PMV dan PPD sebanyak 78% dan 90%. Kajian ini menunjukkan bahawa pemilihan bilangan dan lokasi kipas yang betul dapat meningkatkan keselesaan terma di dalam ruang tertutup yang besar.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ASHRAE	-	American Society of Heating, Refrigerating and Air Conditioning Engineers
PMV	-	Predicted mean vote
PPD	-	Predicted percentage of dissatisfied
CET	-	Corrected Effective Temperature
CFD	-	Computational fluid dynamics
ACH	-	Air change rate
IAQ	-	Indoor air quality
HVAC	-	Heating, ventilating and air-conditioning
AC	-	Air-conditioning
DV	-	Displacement ventilation
UFAD	-	Under floor air distribution
GCI	-	Grid convergence index
GIT	-	Grid independent test
RANS	-	Reynolds-averaged Navier Stokes
SST	-	Shear stress transport
SIMPLE	-	Semi-Implicit Method for Pressure-Linked Equations
3D	-	Three-dimensional
PDE	-	Partial differential equations
RNG	-	Renormalisation group
FVM	-	Finite volume method
MPH	-	Main prayer hall
CBE	-	Center built environment

LIST OF SYMBOLS

$\dot{Q}$	-	Mass Flow rate (m^3/h)
$\dot{V}$	-	Volume flow rate
T_a	-	Air temperature (^{o}c)
V_a	-	Air velocity (m/s)
RH_a	-	Air relative humidity (%)
$T_{mrt.}$	-	Mean radiant temperature (^{o}c)
M	-	Metabolic rate (W/m^2)
W	-	Active work (W/m^2)
L	-	Thermal load
T_{cl}	-	Cloth temperature (°C)
h_c	-	Heat transfer coefficient (W/m^2K)
I_{cl}	-	Sensible heat transfer (m^2K/W).
t	-	Time (s)
D	-	Diameter (m)
D_H	-	Hydraulic diameter (m)
TI	-	Turbulent intensity
A	-	Area of the opening (m^2)
V	-	Volume (m^3)
f_j	-	Mass fraction of species
m_j	-	Mass concentration of species
m_t	-	Total mass concentration of the mixture
S_c	-	Generation rate of concentration.
c	-	Mixture concentration
D_e	-	Diffusion coefficient
P	-	Partial pressure of air (Pa)

P_a	-	Atmospheric pressure (gauge)
P_v	-	Partial pressure of water vapor (Pa)
R	-	Specific gas constant (J/kg.K)
Re	-	Reynolds number
$y+$	-	Dimensionless wall distance
r	-	Refinement ratio
F_s	-	Safety factor
p	-	Order of convergence
ρ	-	Density (kg/m^3)
v	-	Kinematic viscosity (m^2/s)
μ	-	Dynamic viscosity (m^2/s)
σ	-	Standard deviation
C_p	-	Specific heat (J/kg.K)
$T_\circ$	-	Total temperature (^{o}c)
K	-	Thermal conductivity of air (W/m.K)
W^v	-	Viscous work
Q_v	-	Volumetric heat source
ϕ	-	Viscous heat generation
E_k	-	Kinetic energy
∂	-	Differential operator
X, Y, Z	-	Cartesian coordinate

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Thermal comfort is an essential requirement in most occupied spaces because it affects the productivity, health and thermal satisfaction of the occupants. Thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment" [1, 2]. Ventilation is the most conventional cooling method used in many buildings for providing thermal comfort. The ventilation is defined as the “process by which fresh air is introduced and the removal of ventilated air from an occupied space” [3]. The ventilation improves the thermal comfort of occupied areas by providing a heat transport mechanism and lowering the air temperature inside an occupied space [4].

Several types of ventilation can be used to control the air distribution and to provide a thermal comfort in buildings such as natural, mechanical, and hybrid ventilation [5]. Natural ventilation is used to supply outside air into a space through openings such as windows, doors, and ventilations by using natural forces [6]. Mechanical ventilation is the process of supplying and removing air using mechanical devices, such as fans and exhaust vents [7]. Hybrid ventilation provides thermal comfort by using a combination of both natural and mechanical ventilation systems [3, 8]. The typical system that is recommended in the hot and humid climate regions is the natural ventilation [9, 10]. However, it is not capable of providing sufficient level of thermal comfort in all areas, due to the inconsistent wind speed and different climate characteristic.

A mosque is considered as spiritually important buildings in Malaysia and other Islamic countries. It is a place for the Muslims to perform their congregational prayers and other communal religious activities. Thermal comfort inside the mosque is, therefore, a requirement to ensure tranquil comfort to the occupants when performing their activities [11]. However, there is a lack of in-depth study and analysis of thermal comfort inside mosque buildings [11-14].

Modern mosques may be broadly classified according to their sizes and locations [15, 16]. The mosques located in the cities serve as public landmarks. They are usually large in size and can accommodate very large number of peoples. Medium size mosques are located in urban and rural areas. They often have facilities such as libraries, schools, meeting rooms, clinics, etc. They are usually utilized for both daily congregational as well as Friday prayers. They are supplemented with a separate annex on the same floor level or in a mezzanine for the females. There are many smaller size mosques that are located in smaller neighborhoods.

The commonly used method to provide thermal comfort in many mosques building in Malaysia is natural ventilation and mechanical fans. Based on the data provided by the Malaysian Meteorological Service [17] for 10-years period, the daytime temperature is in the range of 23.7 °C to 31.3°C with the maximum temperature of 36.9°C. The relative humidity is in the range of 67% to 95%. A low wind velocity with an average of 1.5 m/s was recorded throughout the year. The mechanical fans only move the air inside the space but they do not promote exchange of fresh air [12, 18-24]. Hence, the presently used ventilation system is ineffective to provide a satisfactory level of thermal comfort [25]. Therefore, an alternative ventilation strategy is needed.

There are several tools and methods that can be used to study and analyse ventilation system in buildings. These include empirical models, analytical models, zonal models, multi-zone models, small-scale experimental models, full-scale experimental models, and computational fluid dynamics (CFD) [4]. The CFD method is convenient, accurate and widely used in predicting the ventilation performance. The rapid increase in computing capability has made this method even more popular [4, 26, 27]. A combination of CFD analysis and field measurement has been used in many studies to assess the indoor thermal comfort in buildings [28-34]. In this study, a similar approach is employed to evaluate the performance of a proposed ventilation system for a mosque building.

1.2 Problem Statement

In Malaysia climatic conditions, a space-cooling method using natural ventilation and mechanical fans is commonly used to provide thermal comfort in many buildings, including mosques. However, this method may not be enough to provide the required thermal comfort in large buildings and open mosques. Such mosques may suffer from the improper air distribution. This irregular air distribution may lead to an increase in temperature. In some parts of the space the airflow velocity may not be enough to assure proper circulation of the air through the whole area. Deficiency of the ventilation system of the mosque especially during Friday prayers, where increase in the number of occupants leads to worsening the problem. Installing suitable exhaust fans is a reasonable approach for replacing and supporting the conventional fans to improve the thermal comfort. The main objective of this study is to improve the thermal comfort inside the Al-Jawahir Mosque that located in Johor Bahru, Malaysia by using exhaust fans. Two approaches were used in this study namely field measurement and CFD simulation. The field measurements were carried out to measure the airflow velocity, air relative humidity, air temperature and mean radiant temperature inside the mosque. A simplified CFD model of the mosque was developed and validated based on the measured airflow velocity, air temperature and air relative humidity. The CFD flow simulations were conducted to find the most suitable location and number of exhaust fans that would result in the greatest improvement in the thermal comfort inside the mosque.

1.3 Objectives

The goal of this study is to improve the thermal comfort inside the Al-Jawahir Mosque that located in Johor Bahru, Malaysia by using exhaust fans.

The research objectives are:

1. To evaluate the effectiveness of the current ventilation system in providing thermal comfort in the mosque.
2. To examine the effect of installing exhaust fans on the thermal comfort inside the mosque by using the CFD method.
3. To find the most suitable location and number of exhaust fans that would result in the greatest improvement in the thermal comfort inside the mosque by using the CFD method.

1.4 Scope of Study

The scopes of this study are as follows:

1. Due to the diversity of mosque types with respect to their size, it was found necessary to limit this study to the medium-size mosque building.
2. The case study is on the Al-Jawahir Mosque, which is located in Johor Bahru, Malaysia.
3. The thermal comfort parameters considered during the field measurement are air temperature, airflow velocity, air relative humidity, and mean radiant temperature.
4. The thermal comfort indices considered are Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD).
5. The CFD analyses were carried out in steady-state conditions.
6. An exhaust fan with a diameter of 1.0 m was chosen. This diameter is mostly available in the market. It also fits well into the wall and roof sections of the prayer hall envelope.

1.5 Significance of Research

This study introduces new ventilation system to improve the thermal comfort inside the mosque by using exhaust fans. The thermal comfort inside the mosque will ensure tranquil comfort to the occupants when performing their activities. The study can also be used as a guideline for improving thermal comfort in mosques under construction in hot and humid climates.

1.6 Thesis Outline

This thesis contains five chapters including the present chapter, which covers the introduction, problem statement, objectives and scopes of this research.

Chapter 2 reviews and discusses the previous studies related to this research, to provide a basis for conducting this research. The report includes information on thermal comfort, factors affecting thermal comfort and the thermal comfort studies in hot and humid tropical countries. Also, this chapter discusses the different types of ventilation system used to improve thermal comfort in the building. Moreover, the concept of medium space buildings and mosques are discussed. Furthermore, this chapter discusses the different tools and method used to study and analyse the ventilation in buildings.

Chapter 3 presents the methodology applied to this research. It includes a field measurement and CFD simulation analysis. This section also describes the development of the numerical simulation of a three-dimensional mosque model by using CFD FLUENT software. Also, the validation and sensitivity analysis procedure of the CFD model are deeply discussed. Five cases of parametric analysis are presented in this chapter.

In Chapter 4, the results of field measurements and CFD simulation on thermal comfort are presented. This chapter also discusses the results of the baseline case and parametric study are presented concerning contours of air temperature, airflow velocity and air relative humidity as well as air flow patterns at steady-state conditions. Also, this chapter discusses the effects of the exhaust fan number and location on the air temperature, airflow distribution, relative humidity and thermal comfort inside the mosque. This chapter concluded the significant findings of the study.

Finally, the conclusions and several recommendations for future work are presented in Chapter 5.

REFERENCES

1. Standard, A. Standard 55-2013. Thermal environmental conditions for human occupancy. ASHRAE. *Atlanta, USA*. 2013.
2. Fanger, P. Assessment of man's thermal comfort in practice. *British journal of industrial medicine*. 1973. 30(4): 313-324.
3. Heiselberg, P., Murakami, S. and Roulet, C.-A. Ventilation of large spaces in buildings. *Final Report IEA Annex*. 1998. 26.
4. Chen, Q. Ventilation performance prediction for buildings: A method overview and recent applications. *Building and Environment*. 2009. 44(4): 848-858.
5. Cao, G., Awbi, H., Yao, R., Fan, Y., Sirén, K., Kosonen, R. and Zhang, J. J. A review of the performance of different ventilation and airflow distribution systems in buildings. *Building and Environment*. 2014. 73: 171-186.
6. Elzaidabi, A. A. M. *Low energy, wind catcher assisted indirect-evaporative cooling system for building applications*. University of Nottingham; 2009.
7. Abdullah, A. H. *A study on thermal environment performance in atria in the tropics with special reference to Malaysia*. Heriot-Watt University; 2007.
8. Wouters, P., Heijmans, N., Delmotte, C. and Vandaele, L. Classification of hybrid ventilation concepts. *IEA Annex*. 1999. 35.
9. Kubota, T., Chyee, D. T. H. and Ahmad, S. The effects of night ventilation technique on indoor thermal environment for residential buildings in hot-humid climate of Malaysia. *Energy and Buildings*. 2009. 41(8): 829-839.
10. Rahman, A. M. A., Khalid, H. L. and Yusup, Y. Optimizing Wind Power for Energy Efficient Building Design in Tropical Hot-humid Climate of Malaysia. *Journal of Sustainable Development*. 2011. 4(2): p217.
11. Ibrahim, S., Baharum, A., Nawi, M. and Junaidi, E. Assessment of thermal comfort in the mosque in Sarawak, Malaysia. *International Journal of Energy and Environment*. 2014. 5(3): 327-334.

12. Al-Homoud, M. S., Abdou, A. A. and Budaiwi, I. M. Assessment of monitored energy use and thermal comfort conditions in mosques in hot-humid climates. *Energy and Buildings*. 2009. 41(6): 607-614.
13. Bakhlah, M. S. and Hassan, A. S. The study of air temperature when the sun path direction to Ka'abah: with a case study of Al-Malik Khalid Mosque, Malaysia. *International Transaction Journal of Engineering, Management & Applied Sciences & Technologies*. 2012. 3(2): 185-202.
14. Saeed, S. Thermal comfort requirements in hot dry regions with special reference to Riyadh part 2: for Friday prayer. *International journal of ambient energy*. 1996. 17(1): 17-21.
15. Abdou, A., Al-Homoud, M. and Budaiwi, I. Mosque Energy Performance, Part I: Energy Audit and Use Trends Based on the Analysis of Utility Billing Data. *King Abdulaziz Journal for Science and Engineering, JKAU: Eng. Sci*. 2005. 16(1).
16. Serageldin, I. and Steele, J. *Architecture of the contemporary mosque*: John Wiley & Son Ltd. 1996.
17. Hussein, I., Rahman, M. H. A. and Maria, T. Field studies on thermal comfort of air-conditioned and non air-conditioned buildings in Malaysia. Proceedings of the *Energy and Environment, 2009. ICEE 2009. 3rd International Conference on*: IEEE. 360-368.
18. Raja, I. A., Nicol, J. F., McCartney, K. J. and Humphreys, M. A. Thermal comfort: use of controls in naturally ventilated buildings. *Energy and Buildings*. 2001. 33(3): 235-244.
19. Zhai, Y., Zhang, H., Zhang, Y., Pasut, W., Arens, E. and Meng, Q. Comfort under personally controlled air movement in warm and humid environments. *Building and Environment*. 2013. 65: 109-117.
20. Wong, N. H., Song, J. and Istiadji, A. D. A study of the effectiveness of mechanical ventilation systems of a hawker center in Singapore using CFD simulations. *Building and Environment*. 2006. 41(6): 726-733.
21. Lee, S. and Chang, M. Indoor and outdoor air quality investigation at schools in Hong Kong. *Chemosphere*. 2000. 41(1): 109-113.
22. Khedari, J., Yamtraipat, N., Pratintong, N. and Hirunlabh, J. Thailand ventilation comfort chart. *Energy and buildings*. 2000. 32(3): 245-249.

23. Atthajariyakul, S. and Lertsatittanakorn, C. Small fan assisted air conditioner for thermal comfort and energy saving in Thailand. *Energy Conversion and Management*. 2008. 49(10): 2499-2504.

24. Sekhar, S. Space temperature difference, cooling coil and fan—energy and indoor air quality issues revisited. *Energy and buildings*. 2005. 37(1): 49-54.

25. Chow, W., Fung, W. and Wong, L. Preliminary studies on a new method for assessing ventilation in large spaces. *Building and Environment*. 2002. 37(2): 145-152.

26. Hurnik, M., Blaszczok, M. and Popiolek, Z. Air Distribution Measurement In A Room With A Sidewall Jet: A 3d Benchmark Test For Cfd Validation. *Building and Environment*. 2015.

27. van Hooff, T., Blocken, B., Aanen, L. and Bronsema, B. A venturi-shaped roof for wind-induced natural ventilation of buildings: wind tunnel and CFD evaluation of different design configurations. *Building and Environment*. 2011. 46(9): 1797-1807.

28. Coffey, C. and Hunt, G. Ventilation effectiveness measures based on heat removal: Part 2. Application to natural ventilation flows. *Building and environment*. 2007. 42(6): 2249-2262.

29. Fitzgerald, S. D. and Woods, A. W. The influence of stacks on flow patterns and stratification associated with natural ventilation. *Building and Environment*. 2008. 43(10): 1719-1733.

30. Ji, Y., Cook, M. and Hanby, V. CFD modelling of natural displacement ventilation in an enclosure connected to an atrium. *Building and Environment*. 2007. 42(3): 1158-1172.

31. Juárez, J. O., Hinojosa, J. F., Xamán, J. P. and Tello, M. P. Numerical study of natural convection in an open cavity considering temperature-dependent fluid properties. *International Journal of Thermal Sciences*. 2011. 50(11): 2184-2197.

32. Rajagopalan, P. and Luther, M. B. Thermal and ventilation performance of a naturally ventilated sports hall within an aquatic centre. *Energy and Buildings*. 2013. 58: 111-122.

33. Hajdukiewicz, M., Geron, M. and Keane, M. M. Calibrated CFD simulation to evaluate thermal comfort in a highly-glazed naturally ventilated room. *Building and Environment*. 2013. 70: 73-89.

34. Gilani, S., Montazeri, H. and Blocken, B. CFD simulation of temperature stratification for a building space: validation and sensitivity analysis. Proceedings of the *Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association, Chambéry, France, August*. 26-28.

35. Szokolay, S. V. *Introduction to architectural science: the basis of sustainable design*: Routledge. 2014.

36. Maarof, S. *Roof designs and affecting thermal comfort factors in a typical naturally ventilated Malaysian mosque*. Cardiff University; 2014.

37. Handbook, A. American Society of Heating. *Refrigeration and Air-Conditioning Engineers, Inc*. 2005.

38. Ibrahim, S., Baharun, A., Nawi, M. and Junaidi, E. Analytical Studies on Levels of Thermal Comfort in Typical Low-Income Houses Design. *UNIMAS e-Journal of Civil Engineering*. 2014. 5(1).

39. Iso, E. 7730: 2005:"Ergonomics of the thermal environment–Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria". *International Organization for Standardisation, Geneva*. 2005.

40. Al-ajmi, F. F. and Loveday, D. L. Indoor thermal conditions and thermal comfort in air-conditioned domestic buildings in the dry-desert climate of Kuwait. *Building and Environment*. 2010. 45(3): 704-710.

41. Djongyang, N., Tchinda, R. and Njomo, D. Thermal comfort: A review paper. *Renewable and Sustainable Energy Reviews*. 2010. 14(9): 2626-2640.

42. Hussin, A., Salleh, E., Chan, H. and Mat, S. Thermal Comfort during daily prayer times in an Air-Conditioned Mosque in Malaysia. 2014.

43. De Dear, R. and Leow, K. Indoor climate and thermal comfort in high-rise public housing in an equatorial climate: a field-study in Singapore. *Atmospheric Environment. Part B. Urban Atmosphere*. 1990. 24(2): 313-320.

44. Rahman, A. M. A. Housing design in relation to environmental comfort: A comparison of the traditional Malay house and modern housing including work in the tripartite programme between Universiti Sains Malaysia, the

Welsh School of Architecture and the UK building research establishment. *Building research and information*. 1995. 23(1): 49-54.

45. Zainal, M. and Keong, C. Thermal comfort and energy conservation in factory buildings. Proceedings of the *Proceedings of the 7th international conference on Indoor Air Quality and Climate*. 1996. 601-606.

46. Nicol, J. F., Raja, I. A., Allaudin, A. and Jamy, G. N. Climatic variations in comfortable temperatures: the Pakistan projects. *Energy and Buildings*. 1999. 30(3): 261-279.

47. Rahman, A. M. A., Malaysia, U. S., Perumahan, P. P. and dan Perancangan, B. *Usaha-usaha mencapai keselesaan terma dalaman di Malaysia*: Penerbit Universiti Sains Malaysia bagi Pihak Pusat Pengajian Perumahan, Bangunan, dan Perancangan. 2000.

48. Sapian, A., Madros, N. and Ahmad, M. Evaluation of thermal comfort performance in low cost flats: case study of Sri Perak flats, Kuala Lumpur. *Development of passive solar design and technology in tropical climates*. 2001.

49. Wong, N. H. and Khoo, S. S. Thermal comfort in classrooms in the tropics. *Energy and buildings*. 2003. 35(4): 337-351.

50. Zain, Z. M., Taib, M. N. and Baki, S. M. S. Hot and humid climate: prospect for thermal comfort in residential building. *Desalination*. 2007. 209(1-3): 261-268.

51. Azizpour, F., Moghimi, S., Lim, C., Mat, S., Zaharim, A. and Sopian, K. Thermal comfort assessment in large scale hospital: Case study in Malaysia. Proceedings of the *Proceedings of the 4th WSEAS international conference on Energy and development-environment-biomedicine*: World Scientific and Engineering Academy and Society (WSEAS). 2011. 171-174.

52. Axley, J. W. Application of Natural Ventilation for US Commercial Buildings–Climate Suitability, Design Strategies & Methods, Modeling Studies. *Gaithersburg, MD, NIST*. 2001.

53. Hani, A., Kõiv, T.-A. and Mikola, A. Ventilating with room units in educational institutions. *International Journal of Energy and Environment*. 2011. 5(5): 629-636.

54. Emmerich, S. Simulated Performance of Natural and Hybrid Ventilation Systems in an Office Building. *HVAC&R Research*. 2006. 12(4): 975-1004.

55. Chow, W. K. Wind-induced indoor-air flow in a high-rise building adjacent to a vertical wall. *Applied Energy*. 2004. 77(2): 225-234.

56. Etheridge, D. *Natural Ventilation of Buildings Theory, Measurement and Design*, Chichester: John Wiley & Sons, Ltd. 2012.

57. Ji, Y., Lomas, K. J. and Cook, M. J. Hybrid ventilation for low energy building design in south China. *Building and Environment*. 2009. 44(11): 2245-2255.

58. Lomas, K. J., Cook, M. J. and Fiala, D. Low energy architecture for a severe US climate: design and evaluation of a hybrid ventilation strategy. *Energy and Buildings*. 2007. 39(1): 32-44.

59. Roberson, J. A., Brown, R. E., Koomey, J. G. and Greenberg, S. E. *Recommended ventilation strategies for energy-efficient production homes*: Ernest Orlando Berkeley National Laboratory, University of California. 1998.

60. Ghiaus, C. and Roulet, C.-A. Strategies for natural ventilation. In: Ghiaus, C. and Allard, F. eds. *Natural Ventilation in the Urban Environment: Assessment and Design*. London: Earthscan. 136-157; 2005.

61. Heiselberg, P. Design of natural and hybrid ventilation. Department of Civil Engineering, Aalborg University. 2006.

62. Kim, M.-H. and Hwang, J.-H. Performance prediction of a hybrid ventilation system in an apartment house. *Energy and Buildings*. 2009. 41(6): 579-586.

63. Hong, S. W., Lee, I. B., Seo, I. H. and Kwon, K. S. The design and testing of a small-scale wind turbine fitted to the ventilation fan for a livestock building. *Computers and Electronics in Agriculture*. 2013. 99: 65-76.

64. Penders, S., Loomans, M., Rutten, P. and Hensen, J. Modelling and simulation of a jet fan for controlled air flow in large enclosures. *Environmental Modelling & Software*. 2011. 26(2): 191-200.

65. Rahman, A. M. A., Khalid, H. L. and Yusup, Y. Optimizing Wind Power for Energy Efficient Building Design in Tropical Hot-humid Climate of Malaysia. *Journal of Sustainable Development*. 2011. 4(2): 217.

66. Etheridge, D. *Natural ventilation of buildings: theory, measurement and design*: John Wiley & Sons. 2011.

67. Hussein, I., Rahman, M. and Maria, T. Field studies on thermal comfort of air-conditioned and non air-conditioned buildings in Malaysia. Proceedings of the *Energy and Environment, 2009. ICEE 2009. 3rd International Conference on*: IEEE. 360-368.

68. Ho, S., Rosario, L. and Rahman, M. Effect of Using Ceiling Fan on Human Thermal Comfort in Air-Conditioned Space. 2005. 10.2514/6.2005-5734.

69. Bassiouny, R. and Korah, N. S. Studying the features of air flow induced by a room ceiling-fan. *Energy and Buildings*. 2011. 43(8): 1913-1918.

70. Ho, S. H., Rosario, L. and Rahman, M. M. Thermal comfort enhancement by using a ceiling fan. *Applied Thermal Engineering*. 2009. 29(8-9): 1648-1656.

71. Niachou, K., Hassid, S., Santamouris, M. and Livada, I. Experimental performance investigation of natural, mechanical and hybrid ventilation in urban environment. *Building and Environment*. 2008. 43(8): 1373-1382.

72. Lin, J.-T. and Chuah, Y. K. A study on the potential of natural ventilation and cooling for large spaces in subtropical climatic regions. *Building and Environment*. 2011. 46(1): 89-97.

73. Zhang, Y. and Zhao, B. Simulation and health risk assessment of residential particle pollution by coal combustion in China. *Building and Environment*. 2007. 42(2): 614-622.

74. Yuying, F., Chen, H., Xin, W., Xing, L. and Sheng, L. Study on the Application of Hybrid System in a Large Space Building. Proceedings of the *Energy and Environment Technology, 2009. ICEET'09. International Conference on*: IEEE. 365-368.

75. Alan Short, C. and Lomas, K. J. Exploiting a hybrid environmental design strategy in a US continental climate. *Building Research and Information*. 2007. 35(2): 119-143.

76. Gomaa, E. S. M., Khalil, E. E., Fouad, M. and Medhat, A. Design of the Ventilation System in an Underground Car Park: Local Mean Age of Air. Proceedings of the *13th International Energy Conversion Engineering Conference*. 2015. 4243.

77. Wong, N., Song, J. and Istiadji, A. A study of the effectiveness of mechanical ventilation systems of a hawker center in Singapore using CFD simulations. *Building and environment*. 2006. 41(6): 726-733.

78. Hamlyn, D., Cash, P. D., Still, M. G., Armitage, P. and Fitzgerald, S. Ventilation Approaches for Shopping Malls–An Examination of Natural and Hybrid Strategies. *ASHRAE Transactions*. 2012. 118(1).

79. Ocak, Y., Kılıçvuran, A., Eren, A. B., Sofuoglu, A. and Sofuoglu, S. C. Exposure to particulate matter in a mosque. *Atmospheric Environment*. 2012. 56: 169-176.

80. Al-Dabbous, A., Khan, A., Al-Rashidi, M. and Awadi, L. Carbon dioxide and volatile organic compounds levels in mosque in hot arid climate. *Indoor and Built Environment*. 2013. 22(2): 456-464.

81. Soegijanto, F. N. S. a. T. Y. Study on Thermal Comfort in Istiqlal Mosque. 2004.

82. Lin, Z., Chow, T., Tsang, C., Fong, K. and Chan, L. CFD study on effect of the air supply location on the performance of the displacement ventilation system. *Building and environment*. 2005. 40(8): 1051-1067.

83. Calay, R., Borresen, B. and Holdø, A. Selective ventilation in large enclosures. *Energy and buildings*. 2000. 32(3): 281-289.

84. Xu, T. T., Carrié, F. R., Dickerhoff, D. J., Fisk, W. J., McWilliams, J., Wang, D. and Modera, M. P. Performance of thermal distribution systems in large commercial buildings. *Energy and buildings*. 2002. 34(3): 215-226.

85. Abdou, A., Al-Homoud, M., Budaiwi, I. and Khaiyat, S. A systematic approach for energy audit in mosques. Proceedings of the *Proc. 2nd International Conference on Energy Research and Development*. 2002. 77-86.

86. Abdou, A., Al-Homoud, M. and Budaiwi, I. Mosque energy performance, part I: energy audit and use trends based on the analysis of utility billing data. *Engineering Sciences*. 2005. 16(1).

87. Hameed, A. N. A. Thermal Comfort Assessment to Building Envelope: A Case Study for New Mosque Design in Baghdad. 2011.

88. Al-Homoud, M. S. Thermal Design Optimization of Mosques in Saudi Arabia. Proceedings of the *Proceedings of the International Symposium on Mosque Architecture*. 1999. 15-30.

89. Budaiwi, I. M. Envelope thermal design for energy savings in mosques in hot-humid climate. *Journal of Building Performance Simulation*. 2011. 4(1): 49-61.

90. Kim, G., Schaefer, L., Lim, T. S. and Kim, J. T. Thermal comfort prediction of an underfloor air distribution system in a large indoor environment. *Energy and Buildings*. 2013. 64: 323-331.

91. Nielsen, P. V., Allard, F., Awbi, H. B., Davidson, L. and Schälin, A. Computational Fluid Dynamics in Ventilation Design REHVA Guidebook No 10. *International Journal of Ventilation*. 2007. 6(3): 291-293.

92. Janssen, W., Blocken, B. and van Hooff, T. Pedestrian wind comfort around buildings: Comparison of wind comfort criteria based on whole-flow field data for a complex case study. *Building and Environment*. 2013. 59: 547-562.

93. Montazeri, H. and Blocken, B. CFD simulation of wind-induced pressure coefficients on buildings with and without balconies: validation and sensitivity analysis. *Building and environment*. 2013. 60: 137-149.

94. van Hooff, T., Blocken, B., Aanen, L. and Bronsema, B. Numerical analysis of the performance of a venturi-shaped roof for natural ventilation: influence of building width. *Journal of Wind Engineering and Industrial Aerodynamics*. 2012. 104: 419-427.

95. Ji, Y., Cook, M. J. and Hanby, V. CFD modelling of natural displacement ventilation in an enclosure connected to an atrium. *Building and Environment*. 2007. 42(3): 1158-1172.

96. Lau, J. and Chen, Q. Floor-supply displacement ventilation for workshops. *Building and Environment*. 2007. 42(4): 1718-1730.

97. Wu, X. and Li, X. Numerical Simulation of Displacement Ventilation in a Gymnasium in a Large Space Building. 2006.

98. Ho, S. H., Rosario, L. and Rahman, M. M. Three-dimensional analysis for hospital operating room thermal comfort and contaminant removal. *Applied Thermal Engineering*. 2009. 29(10): 2080-2092.

99. Blanes-Vidal, V., Guijarro, E., Balasch, S. and Torres, A. Application of computational fluid dynamics to the prediction of airflow in a mechanically ventilated commercial poultry building. *Biosystems Engineering*. 2008. 100(1): 105-116.

100. Lam, J. C. and Chan, A. L. CFD analysis and energy simulation of a gymnasium. *Building and Environment*. 2001. 36(3): 351-358.

101. Song, J. and Meng, X. The Improvement of Ventilation Design in School Buildings Using CFD Simulation. *Procedia Engineering*. 2015. 121: 1475-1481.

102. Tap, M. M., Kamar, H. M., Marsono, A. K., Kamsah, N. and Salimin, K. A. M. Simulation of Thermal Comfort of a Residential House. *International Journal of Computer Science Issues (IJCSI)*. 2011. 8(5).

103. Yin, Y., Xu, W., Gupta, J. K., Guity, A., Marmion, P., Manning, A., Gulick, B., Zhang, X. and Chen, Q. Experimental study on displacement and mixing ventilation systems for a patient ward. *HVAC&R Research*. 2009. 15(6): 1175-1191.

104. Curi, T. M. d. C., Moura, D. J. d., Massari, J. M., Mesquita, M. and Pereira, D. F. Computational fluid dynamics (CFD) application for ventilation studies in broiler houses. *Engenharia Agrícola*. 2017. 37(1): 1-12.

105. Gaitani, N., Mihalakakou, G. and Santamouris, M. On the use of bioclimatic architecture principles in order to improve thermal comfort conditions in outdoor spaces. *Building and Environment*. 2007. 42(1): 317-324.

106. Hughes, I. and Hase, T. *Measurements and their uncertainties: a practical guide to modern error analysis*: Oxford University Press. 2010.

107. Annoni, M. Water jet velocity uncertainty in laser Doppler velocimetry measurements. *Measurement*. 2012. 45(6): 1639-1650.

108. Taylor, B. N. *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results (rev*: DIANE Publishing. 2009.

109. Younes, C. and Shdid, C. A. A methodology for 3-D multiphysics CFD simulation of air leakage in building envelopes. *Energy and Buildings*. 2013. 65: 146-158.

110. Setaih, K., Hamza, N., Mohammed, M., Dudek, S. and Townshend, T. CFD modeling as a tool for assessing outdoor thermal comfort conditions in urban settings in hot arid climates. ITcon. 2014.

111. Eça, L. and Hoekstra, M. A procedure for the estimation of the numerical uncertainty of CFD calculations based on grid refinement studies. *Journal of Computational Physics*. 2014. 262: 104-130.

112. Zhang, Z. and Chen, Q. Comparison of the Eulerian and Lagrangian methods for predicting particle transport in enclosed spaces. *Atmospheric Environment*. 2007. 41(25): 5236-5248.

113. Roache, P. J. Perspective: a method for uniform reporting of grid refinement studies. *Journal of Fluids Engineering*. 1994. 116(3): 405-413.

114. Ali, M. S. M., Doolan, C. J. and Wheatley, V. Grid convergence study for a two-dimensional simulation of flow around a square cylinder at a low Reynolds number. Proceedings of the *7th International Conference on CFD in the Minerals and Process Industries CSIRO, C. Doolan and V. Wheatley, eds., Melbourne, Australia, Dec*. 2009. 9-11.

115. Roache, P. J. Error bars for CFD. Proceedings of the *AIAA 41st Aerospace Sciences Meeting*. 2003-0408.

116. Celik, I. B., Ghia, U. and Roache, P. J. Procedure for estimation and reporting of uncertainty due to discretization in {CFD} applications. *Journal of fluids {Engineering-Transactions} of the {ASME}*. 2008. 130(7).

117. Calautit, J. K., O'Connor, D., Sofotasiou, P. and Hughes, B. R. CFD simulation and optimisation of a low energy ventilation and cooling system. *Computation*. 2015. 3(2): 128-149.

118. Fluent, A. ANSYS fluent user's guide, release 14.0. *PA: ANSYS Fluent*. 2011.

119. Villafruela, J., Olmedo, I., de Adana, M. R., Méndez, C. and Nielsen, P. V. CFD analysis of the human exhalation flow using different boundary conditions and ventilation strategies. *Building and Environment*. 2013. 62: 191-200.

120. Fluent, A. 14.0 User's Manual. *ANSYS Inc., Canonsburg, PA*. 2011.

121. Committee, A. S. ASHRAE handbook: fundamentals 2013. Ashrae. 2013.

122. McQuiston, F. C. and Parker, J. D. Heating, ventilating, and air conditioning: analysis and design. 1982.

123. Prakash, D. and Ravikumar, P. Analysis of thermal comfort and indoor air flow characteristics for a residential building room under generalized window opening position at the adjacent walls. *International Journal of Sustainable Built Environment*. 2015. 4(1): 42-57.

124. Gao, Z. and Zhang, J. Numerical analysis for evaluating the “Exposure Reduction Effectiveness” of room air cleaners. *Building and Environment*. 2010. 45(9): 1984-1992.

125. Tung, Y.-C., Shih, Y.-C. and Hu, S.-C. Numerical study on the dispersion of airborne contaminants from an isolation room in the case of door opening. *Applied Thermal Engineering*. 2009. 29(8): 1544-1551.

126. Ramponi, R. and Blocken, B. CFD simulation of cross-ventilation flow for different isolated building configurations: validation with wind tunnel measurements and analysis of physical and numerical diffusion effects. *Journal of Wind Engineering and Industrial Aerodynamics*. 2012. 104: 408-418.

127. Franke, J., Hellsten, A., Schlunzen, H. and Carissimo, B. The Best Practise Guideline for the CFD simulation of flows in the urban environment: an outcome of COST 732. Proceedings of the *The Fifth International Symposium on Computational Wind Engineering. Chapel Hill, North Carolina, USA*. 2010.

128. Srebric, J. and Chen, Q. An example of verification, validation, and reporting of indoor environment CFD analyses. *ASHRAE Transactions*. 2002. 108: 185.

129. Posner, J., Buchanan, C. and Dunn-Rankin, D. Measurement and prediction of indoor air flow in a model room. *Energy and buildings*. 2003. 35(5): 515-526.

130. Oberkampf, W. L. and Trucano, T. G. Verification and validation in computational fluid dynamics. *Progress in Aerospace Sciences*. 2002. 38(3): 209-272.

131. Hussain, S. and Oosthuizen, P. H. Validation of numerical modeling of conditions in an atrium space with a hybrid ventilation system. *Building and Environment*. 2012. 52: 152-161.

132. Ramponi, R. and Blocken, B. CFD simulation of cross-ventilation for a generic isolated building: impact of computational parameters. *Building and Environment*. 2012. 53: 34-48.

133. Hussain, S., Oosthuizen, P. H. and Kalendar, A. Evaluation of various turbulence models for the prediction of the airflow and temperature distributions in atria. *Energy and Buildings*. 2012. 48: 18-28.

134. Blocken, B., Janssen, W. and van Hooff, T. CFD simulation for pedestrian wind comfort and wind safety in urban areas: General decision framework

and case study for the Eindhoven University campus. *Environmental Modelling & Software*. 2012. 30: 15-34.

135. Zhang, Z., Chen, X., Mazumdar, S., Zhang, T. and Chen, Q. Experimental and numerical investigation of airflow and contaminant transport in an airliner cabin mockup. *Building and Environment*. 2009. 44(1): 85-94.

136. Akbari, K. *Impact of Radon Ventilation on Indoor Air Quality and Building Energy saving*. Mälardalen University; 2009.

137. Anand, Y., Gupta, A., Tyagi, S. and Anand, S. Computational fluid dynamics, a building simulation tool for achieving sustainable buildings. *Renewable and Sustainable Energy Reviews*. 2016. 57: 1174-1185.

138. Sanusi, A. N. Z. Low Energy Ground Cooling System for Buildings in Hot and Humid Malaysia. 2012.

139. Hussain, S. Numerical Investigations of the Indoor Thermal Environment in Atria and of the Buoyancy-Driven Ventilation in a Simple Atrium Building. 2012.

140. Tao, H. G., Chen, H. X., Xie, J. L. and Jiang, J. Z. Comparison on simulation and experiment of supply air through metro vehicle air conditioning duct. Proceedings of the *Applied Mechanics and Materials*: Trans Tech Publ. 2011. 1724-1728.

141. Woloszyn, M., Kalamees, T., Abadie, M. O., Steeman, M. and Kalagasidis, A. S. The effect of combining a relative-humidity-sensitive ventilation system with the moisture-buffering capacity of materials on indoor climate and energy efficiency of buildings. *Building and Environment*. 2009. 44(3): 515-524.