

**EFFECT OF WATER IN BUILDING PASSIVE COOLING  
STRATEGIES: A CASE OF SHISH MAHAL COMPLEX  
OF MUGHALS**

**BY**

**MUSTAFFA KAMAL BIN MOHD FAUZI**

**A thesis submitted in fulfilment of the requirement for the  
degree of Master of Science (Built Environment)**

**Kulliyyah of Architecture and Environmental Design  
International Islamic University Malaysia**

**OCTOBER 2020**

## ABSTRACT

Water, in modern cities, is often seen as an infrastructural asset, rather than analyzed, appreciated, and inserted in urban context in its morphological, architectural, and environmental dimensions. This thesis studies the water elements of 16<sup>th</sup>-century Mughal building complexes, with a focus on the Shish Mahal Complex of Lahore Fort, which is argued as a kind of peak or apotheosis of Mughal architecture-based water systems. By looking at both urban-morphological and architectural-engineering dimension, it re-engages with the holistic nature of Mughal architecture in which water systems is seen in its spiritual, aesthetic, and environmental dimension. It then focuses on the environmental analysis of one feature- the coupling of water with thermal mass system of the basement of Shish Mahal, to study its modeling mechanisms and the potential passive impact of the coupling of thermal mass and water elements under such hot arid climate. This was done and further simulated and visualizes the actual indoor thermal condition of the basement of Shish Mahal if the water elements are not present. A fieldwork measurement of Shish Mahal Complex is conducted and acquired for Computational Fluid Dynamics (CFD) ANSYS Fluent simulation process. The thesis contributes to a narrative that investigates both the historical and analytical 'performance-based' perspective, in which the 'morphological' form and shape of the 2 and 3-dimensional shape are initially discussed, and then the impact of water in buildings are studied as a combination of vertical waterwalls and horizontal pools to verify its climatic performance. It is found that the coupling of waterwall with thermal mass will result 8°C to 18°C in reduction to the indoor temperature under hot arid climate conditions when the outdoor temperature rises to 40 °C without resorting to any mechanical cooling. The results also demonstrated that the exploitation of low mean airspeed of 0.5 m/s provides a significant contribution to decrease the indoor temperature. Low mean airspeed provides ample time for the evaporative cooling of the indoor environment to become more efficacious and cooled air to circulate within the premise boundary, this is however work if cross-ventilation strategy is adopted at the same time.

## خلاصة البحث

غالبًا ما يُنظر إلى المياه ، في المدن الحديثة ، على أنها أحد أصول البنية التحتية ، بدلاً من تحليلها وتقديرها وإدراجها في السياق الحضري بعادها المورفولوجية والمعمارية والبيئية. تدرس هذه الأطروحة عناصر المياه في مجتمعات المباني المغولية في القرن السادس عشر ، مع التركيز على مجمع شيش محل في قلعة لاهور ، والذي يُقال إنه نوع من ذروة أو ليه أنظمة المياه القائمة على العمارة المغولية. من خلال النظر إلى كل من البعد الحضري المورفولوجي والهندسة المعمارية ، فإنه يعيد المشاركة مع الطبيعة الشاملة للعمارة المغولية التي تُرى فيها أنظمة المياه في أبعادها الروحية والجمالية والبيئية. ثم يركز على التحليل البيئي لميزة واحدة - اقتران الماء بنظام الكتلة الحرارية في الطابق السفلي لشيش محل ، من أجل دراسة آليات النمذجة والتأثير المحتمل لاقتران الكتلة الحرارية وعناصر الماء تحت مثل هذا الجفاف الحار. مناخ. تم القيام بذلك ومزيد من المحاكاة وتصوير الحالة الحرارية الداخلية الفعلية للطابق السفلي من شيش محل إذا لم تكن عناصر المياه موجودة. يتم إجراء القياس الميداني لمجمع شيش محل والحصول عليه من أجل عملية محاكاة ديناميكيات السوائل الحاسوبية ANSYS Fluent (CFD). تساهم الأطروحة في سرد يبحث في المنظور التاريخي والتحليلي "القائم على الأداء" ، حيث تتم مناقشة الشكل والشكل "المورفولوجي" للشكل ثنائي الأبعاد وثلاثي الأبعاد في البداية ، ومن ثم يتم مناقشة ثير الماء في المباني تمت دراستها كمزيج من المسطحات المائية العمودية والبرك الأفقية للتحقق من أدائها المناخي. لقد وجد أن اقتران الجدار المائي لكتلة الحرارية سينتج عنه 8 درجة مئوية إلى 18 درجة مئوية في تقليل درجة الحرارة الداخلية في ظل ظروف المناخ الجاف الحار عندما ترتفع درجة الحرارة الخارجية إلى 40 درجة مئوية دون اللجوء إلى أي تبريد ميكانيكي. أظهرت النتائج أيضًا أن استغلال متوسط سرعة هواء منخفض يبلغ 0.5 م / ث يوفر مساهمة كبيرة في خفض درجة الحرارة داخل المباني. يوفر متوسط سرعة الهواء المنخفضة وقتًا كافيًا للتبريد التبخيري للبيئة الداخلية ليصبح أكثر كفاءة وتبريد الهواء للدوران داخل حدود المبنى ، ومع ذلك فإن هذا العمل إذا تم اعتماد استراتيجيات التهوية المتقاطعة في نفس الوقت.

## 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 thesis for the degree of Master of Science (Built Environment).

.....  
Nurul Syala Binti Abdul Latip  
Supervisor

.....  
Puteri Shireen Binti Jahn Kassim  
Co-Supervisor

I certify that I have 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 thesis for the degree of Master of Science (Built Environment).

.....  
Aniza Binti Abu Bakar  
Internal Examiner

.....  
Mohd Fairuz Bin Shahidan  
External Examiner

This thesis was submitted to the Department of Architecture and is accepted as a fulfilment of the requirement for the degree of Master of Science (Built Environment).

.....  
Srazali Bin Aripin  
Head, Department of Architecture

This thesis was submitted to the Kulliyah of Architecture and Environmental Design, and is accepted as a fulfilment of the requirement for the degree of Master of Science (Built Environment).

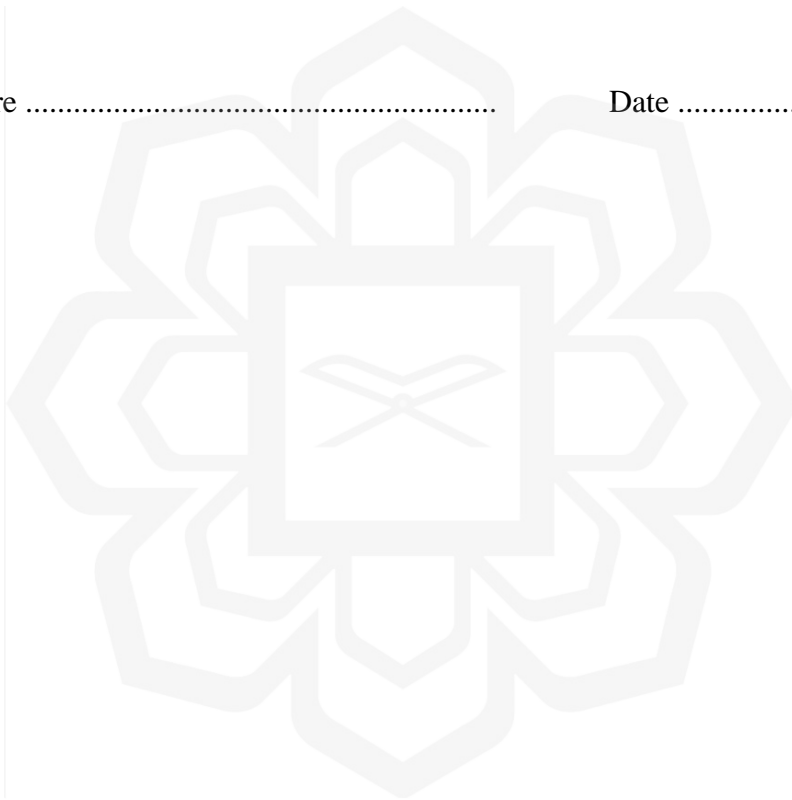
.....  
Abdul Razak Bin Sopian  
Dean, Kulliyah of Architecture  
and Environmental Design

## DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Mustaffa Kamal Bin Mohd Fauzi

Signature ..... Date .....



**INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA**

**DECLARATION OF COPYRIGHT AND AFFIRMATION OF  
FAIR USE OF UNPUBLISHED RESEARCH**

**EFFECT OF WATER IN BUILDING PASSIVE COOLING  
STRATEGIES: A CASE OF SHISH MAHAL COMPLEX OF  
MUGHALS**

I declare that the copyright holders of this thesis are jointly owned by the student and IIUM.

Copyright © 2020 Mustaffa Kamal Bin Mohd Fauzi and International Islamic University Malaysia.  
All rights reserved.

No part of this unpublished research may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise without prior written permission of the copyright holder except as provided below

1. Any material contained in or derived from this unpublished research may be used by others in their writing with due acknowledgement.
2. IIUM or its library will have the right to make and transmit copies (print or electronic) for institutional and academic purposes.
3. The IIUM library will have the right to make, store in a retrieved system and supply copies of this unpublished research if requested by other universities and research libraries.

By signing this form, I acknowledged that I have read and understand the IIUM Intellectual Property Right and Commercialization policy.

Affirmed by Mustaffa Kamal Bin Mohd Fauzi

.....  
Signature

.....  
Date

## ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitude to Allah S.W.T, for bestowing on me with great perseverance, good health, strength and courage in completing the journey of my study and successful in completing this thesis.

I would like to express my highest gratitude to my supervisor Dr. Nurul Syala Abdul Latip whom without her insights, encouragement, guidance, and support from the beginning to the end, I would not have able to come this far. I am indebted to her for the patience and continuous support throughout the period of this study. This thesis would also not have been possible if not for the help from my co-supervisor, Assoc. Prof. Dr. Puteri Shireen Jahn Kassim who showered her strong commitment, continuous support, encouragement and wise thoughtful from the initial stage to the final stage of this study. Her deep knowledge and sharp insight on the research never fail to mesmerize me. Learning from both of my supervisors made my research journey more valuable and adding knowledge on the field of built environment even more broaden.

I would like to express my heartfelt thanks to Prof. Shaukat Mahmood from the University of Punjab Lahore for assisting me in gathering all the required data and surveys of the case study and provides continuous supports throughout the research. Without his support and help, I would never have precise data to the study I conducted. I would also like to express my gratitude to Assoc. Prof. Dr. Yousif Abdalla Abakr for his help in assisting the simulation works and his constant help especially regarding the fluid mechanic engineering.

With deep sense of affection, I would like to acknowledge my parents Mohd Fauzi Thayoob and Shaliha Mohamed for their encouragements, support, du'a and source of love. Also, thank you to my entire brothers, sister, family members and fellow friends. Last but not least, not forgetting to the love of my life, Norfaradila Jaafar for her never-ending support and encouraging me to earn a master's degree. Thank you for all the moral supports and may Allah the Almighty reward you all.

Finally, I wish to express my sincere appreciation and thanks to those who the name did not appear, to provide their time, efforts and support for this research.

# TABLE OF CONTENTS

Abstract .....	ii
Abstract in Arabic .....	iii
Approval page .....	iv
Declaration .....	v
Copyright Page.....	vi
Acknowledgements .....	vii
List of Tables .....	xii
List of Figures .....	xiii
List of Abbreviations .....	xx
List of Symbols .....	xxi
<b>CHAPTER ONE: INTRODUCTION .....</b>	<b>1</b>
1.1 Background of the Study .....	1
1.2 Problem Statement.....	5
1.3 Aim and Objectives .....	6
1.4 Research Questions.....	6
1.5 Scope of Thesis.....	7
1.6 Significance of Thesis.....	8
1.7 Structure of Thesis .....	10
<b>CHAPTER TWO: LITERATURE REVIEW .....</b>	<b>12</b>
2.1 Introduction.....	12
2.2 Passive Cooling: Technique and Strategies .....	12
2.2.1 Classification of Passive Cooling Strategies.....	13
2.2.1.1 Thermal Mass .....	14
2.2.1.2 Evaporative Cooling .....	17
2.3 Water and Evaporative Cooling.....	17
2.3.1 Water as Pool .....	18
2.3.2 Water as Vertical Cooling Strategy .....	18
2.3.3 Roof Spraying as Cooling Strategy.....	19
2.3.4 Evaporative Cooling Tower .....	20
2.4 Water, Passive Cooling and Architectural Spaces.....	20
2.4.1.1 Evaporative Cooling in Specific Sites .....	20
2.5 Building Thermal Dynamics.....	22
2.5.1 Heat Transfer Mechanisms .....	22
2.5.1.1 Conduction.....	23
2.5.1.2 Convection.....	24
2.5.1.3 Radiation.....	26
2.6 Climatic Context of Pakistan .....	26
2.6.1 Lahore Weather Profiles .....	28
2.6.1.1 Temperature (°C) .....	29
2.6.1.2 Humidity (%Rh) .....	30
2.6.1.3 Wind (m/s).....	31
2.7 Thermal Comfort .....	33

2.7.1 Principles of Thermal Comfort .....	33
2.7.2 Factors of Affecting Thermal Comfort .....	35
2.7.2.1 Air Temperature .....	35
2.7.2.2 Relative Humidity.....	35
2.7.2.3 Air Velocity .....	36
2.7.3 Thermal Comfort range in Hot Dry Region.....	37
2.8 Water and Evaporative Cooling in Mughal Complexes .....	38
2.8.1 Historical Overview .....	38
2.8.1.1 Stepwells and its Variation-The Gujarat Baoli.....	38
2.8.1.2 Hydraulic Architecture in Ancient India .....	40
2.8.2 Mechanism of Water Lifting Methods.....	40
2.8.2.1 Fatehpur Sikri An Example .....	43
2.8.3 Water Evaporative Cooling, Urban Design, and Architecture: The Strategies of Mughal Complexes. ....	56
2.8.3.1 From Garden to City.....	57
2.8.3.2 Open-type garden with pools: Fatehpur Sikri and Lahore Fort .....	60
2.8.3.3 Enclosed-type garden with pools: Shish Mahal Complex in Lahore Fort .....	64
2.8.3.4 Shish Mahal Complex of Lahore Fort .....	66
2.8.3.5 Shish Mahal Complex .....	70
2.8.3.6 Cooling Systems of Shish Mahal Courtyard .....	71
2.8.3.7 Shish Mahal Summer Basement.....	80
2.9 Computational Fluid Dynamics (CFD) .....	85
2.9.1 Background .....	85
2.9.2 Turbulence Model .....	86
2.9.3 Boundary Condition and Setting.....	86
2.10 Conclusion .....	87
<b>CHAPTER THREE: METHODOLOGY.....</b>	<b>89</b>
3.1 Introduction.....	89
3.2 Research Design .....	89
3.3 Data Collection .....	90
3.3.1 Literature Review.....	91
3.3.2 Observation .....	91
3.3.3 Fieldwork Measurement .....	92
3.3.4 Objective of Field Measurement.....	92
3.3.5 Selection Area .....	93
3.3.5.1 Measurement locations at the third level (courtyard).....	94
3.3.5.2 Measurement locations at the second level (basement)....	95
3.3.6 Measurements Technique .....	96
3.3.7 Results of Field Measurements .....	100
3.4 CFD (Computational Fluid Dynamic) Modelling .....	104
3.4.1 The Modelling Tool and Software .....	104
3.4.2 Description of Geometry Model .....	106
3.4.3 Meshing.....	108
3.4.4 Boundary Condition.....	110
3.4.5 Governing Equations.....	112
3.4.6 Running Simulation .....	113

3.5 The Simulation Runs .....	114
3.6 Summary .....	115
<b>CHAPTER FOUR: RESULTS AND DISCUSSION .....</b>	<b>116</b>
4.1 Introduction.....	116
4.2 Airflow Results .....	116
4.2.1 Airflow Profile .....	117
4.3 Temperature Variation Through the Central Thermal Mass .....	119
4.4 Results from A Full Year Simulation Run .....	121
4.4.1 January .....	122
4.4.2 February .....	125
4.4.3 March .....	127
4.4.4 April .....	130
4.4.5 May .....	133
4.4.6 June .....	136
4.4.7 July .....	139
4.4.8 August .....	141
4.4.9 September.....	144
4.4.10 October.....	146
4.4.11 November.....	149
4.4.12 December .....	152
4.5 The Effect of Coupling of Waterwalls and Thermal Mass.....	155
4.6 Air Velocity and Evaporative Cooling Effectiveness.....	157
4.7 Detailed Results for Hottest Month (June) .....	159
4.7.1 Overview .....	159
4.7.2 Temperature Profile .....	159
4.8 Relationship Between Temperature Differences to Air Velocity.....	161
4.9 Significance of Water Presence .....	162
4.9.1 Discussions.....	164
4.10 Summary.....	165
<b>CHAPTER FIVE: CONCLUSION .....</b>	<b>167</b>
5.1 Introduction.....	167
5.2 Summary of the Study .....	167
5.3 Review of Objectives.....	169
5.3.1 Objective One .....	169
5.3.2 Objective Two.....	170
5.3.3 Objective Three.....	171
5.4 Contributions .....	171
5.5 Limitation of Study.....	172
5.6 Conclusion .....	173
<b>REFERENCES.....</b>	<b>175</b>
APPENDIX A: BAOLI TYPES ACROSS THE INDIAN CONTINENT .....	183
APPENDIX B: FATEHPUR SIKRI, AGRA INDIA .....	192
APPENDIX C1: CROSS-SECTIONAL DIAGRAM OF FATEHPUR SIKRI NORTHERN WATERWORKS .....	193

APPENDIX C2: CROSS-SECTIONAL DIAGRAM OF FATEHPUR SIKRI SOUTHERN WATERWORKS.....	189
APPENDIX D: MUGHAL GENEALOGY CHART .....	194
APPENDIX E: SHISH MAHAL BUILDING MATERIAL REPORT.....	190
APPENDIX F: SHISH MAHAL FIELDWORK MEASUREMENT REPORT .....	191
APPENDIX G1: EVAPORATION UDF .....	228
APPENDIX G2: MOLLIER DIAGRAM.....	229
APPENDIX H: EMAILS .....	230



## LIST OF TABLES

Table 2.1	Various type of building materials that can be found at Shish Mahal complex.	24
Table 2.2	Temperature profile of Lahore (1961-1990)	29
Table 2.3	Lahore rainfall and humidity	31
Table 2.4	Lahore average windspeed	32
Table 2.5	Factors that affecting the thermal comfort	34
Table 2.6	Charbagh morphology configurations and its water to site ratio analysis	59
Table 2.7	Numbers of water features found in Lahore Fort	80
Table 8	Simulation settings	110
Table 9	Thermo-physical properties of the main building materials	111

## LIST OF FIGURES

Figure 2.1	Classification of passive cooling approaches in energy efficient buildings.	14
Figure 2.2	Time lag and decrement factor.	15
Figure 2.3	Illustration of the three modes of thermal transfer in an enclosed space.	23
Figure 2.4	Convection heat transfer involves the combination of conduction and fluid motion.	25
Figure 2.5	Pakistan and its major cities including Lahore.	27
Figure 2.6	Variable climate conditions throughout Pakistan based on Koppen Climate classification. Lahore city situated within warm and semi-arid climate conditions.	28
Figure 2.7	Lahore average high and low temperature graph for 29 years observation.	30
Figure 2.8	Lahore average high and low temperature associated with humidity.	31
Figure 2.9	Lahore wind rose diagram	32
Figure 2.10	Psychrometric chart for Lahore	37
Figure 2.11:	A cross-sectional illustration of Gujarati step well.	40
Figure 2.12:	Shalimar Bagh, Kashmir	41
Figure 2.13	Illustration of the traditional water lifting device known as <i>rehant</i> .	42
Figure 2.14	Fatehpur Sikri from aerial view	43
Figure 2.15	Fatehpur Sikri and its nine fortification gateways and artificial lake.	44
Figure 2.16	Sectional terraced planning of Fatehpur Sikri	45
Figure 2.17	Conceptual illustration depicting <i>Rehant</i> (water wheel) driven by cattle to lift water from lower to higher ground and associated with the aqueducts for distributions.	47
Figure 2.18	Artificial lake as a source of perennial water supply.	49

Figure 2.19	Rainwater harvesting systems at Fatehpur Sikri.	50
Figure 2.20	The run-off systems at Fatehpur Sikri that lead to final tank or <i>kunda</i> at the public complex.	51
Figure 2.21	Schematic illustration depicting stages of water conveyance systems at northern waterworks in Fatehpur Sikri.	52
Figure 2.22	A 3D illustrations of water conveyance systems at north waterworks in Fatehpur Sikri.	52
Figure 2.23	An illustration of northern waterworks of Fatehpur Sikri indicating how the water are distributed from lower ground to the various part of complex.	54
Figure 2.24	Illustration of south waterworks and its reach to the inner part of Fatehpur Sikri complex	55
Figure 2.25	Charbagh divided into four quadrants of gardens and separated by canals.	61
Figure 2.26	<i>Anup Talao</i> pool resembles to the Indian stepwell design. The pool was built to mitigate heat surrounding area to the royal private quarters.	62
Figure 2.27	Interaction between warm air and cool water causes the evaporation of water which lead to decrease in surrounding temperature.	62
Figure 2.28	Jehangir quadrangle in Lahore Fort- the open-garden type	63
Figure 2.29	Shish Mahal courtyard of Lahore Fort	66
Figure 2.30	Aerial view over Lahore Fort showing location of Shish Mahal complex	67
Figure 2.31	Map of Lahore city and location of Ravi River (left); Lahore Fort map showing Shish Mahal complex (Right)	68
Figure 2.32	Major quadrangles that accommodates royal sleeping quarters located at the northeast of the fort.	69
Figure 2.33	Drawing of the western façade of Shish Mahal Complex showing three main floor levels.	70
Figure 2.34	Illustration of Shish Mahal courtyard in 3D wireframe model.	71
Figure 2.35	Overall Shish Mahal courtyard and its surrounding building.	72
Figure 2.36	Overall illustration of Shish Mahal showing systematic continuance of water flow from rooftop to summer basement.	73

Figure 2.37	Miniature ducts seen under the courtyard floor	74
Figure 2.38	Illustration of a cross-sectional cut showing water from rooftop are channeled down via <i>Chadar</i> (waterwall) at the southern loggia.	75
Figure 2.39	The overflow water from pool will enter the northern runnel and thus funnel into the lower level of the complex.	75
Figure 2.40	A close-up 3D illustration of the waterwall chevron patterns.	76
Figure 2.41	Design of the <i>Chadar</i> (waterwalls) are made feasible to magnify the visibility and sounds of water.	76
Figure 2.42	Basins found at one of the sleeping chambers.	77
Figure 2.43	Illustration of the distribution of chilled air through the ice basins facing to the northeast prevailing wind.	78
Figure 2.44	Exploded 3D model of water flow illustration at three floor levels	78
Figure 2.45	A simplified Shish Mahal's vertical and horizontal water elements and its trajectory.	79
Figure 2.46	Isometric wireframe of the summer basement showing the massing of high vaulted spaces.	81
Figure 2.47	Floor plan of Shish Mahal basement showing the private spaces in light green color. Dark color indicates semi private spaces.	82
Figure 2.48	Location of perforated screens at the northwest of the façade.	83
Figure 2.49	Waterwall at the basement and its cistern adjacent to the thermal mass wall.	83
Figure 2.50	Summer basement waterwall and its source form shallow pool	84
Figure 2.51	Location of the windcatchers at the northeast side of the basement	85
Figure 3.1	Research Methodology Framework	90
Figure 3.2	Drawing of the western façade of Shish Mahal Complex showing three main floor levels.	93
Figure 3.3	Field measurements at the courtyard.	95
Figure 3.4	Measurements of the basement height and waterwall inside the basement.	95
Figure 3.5	Sketch plan of Shish Mahal courtyard.	97

Figure 3.6	Sample of measured drawing.	99
Figure 3.7	The laser measure device used during the fieldwork measurement.	100
Figure 3.8	Passive cooling elements at the courtyard and basement	102
Figure 3.9	A 3D wireframe model drawn in AutoCAD before exporting to ANSYS Fluent for simulation.	103
Figure 3.10	3D CAD model of Shish Mahal basement and the simplification process of the building form.	103
Figure 3.11	Simulation methodology flowchart	105
Figure 3.12	Configuration of Shish Mahal basement in CAD.	106
Figure 3.13	Simplified 3D CAD modeling of the basement.	107
Figure 3.14	Imported 3D CAD model into ANSYS Design modeler.	108
Figure 3.15	View of computational mesh over the entire domain of Shish Mahal basement.	109
Figure 3.16	Location of water source on every niched at the central masonry wall in the basement.	113
Figure 4.1	Airflow profile at 2.5m/s	117
Figure 4.2	Airflow profile at 1m/s	118
Figure 4.3	Airflow profile within the chambers at initial velocity of 0.5 m/s	118
Figure 4.4	Temperature profile across the thermal mass at the central basement wall at 2.5 m/s	120
Figure 4.5	Temperature profile across the thermal mass at the central basement wall at 1 m/s	120
Figure 4.6	Temperature profile across the thermal mass at the central basement wall at 0.5 m/s	121
Figure 4.7	Temperature profile for the basement for January at 2.5m/s.	123
Figure 4.8	Temperature profile for the basement for January at 1 m/s.	123
Figure 4.9	Temperature profile for the basement for January at 0.5m/s.	124
Figure 4.10	Temperature profile of the basement during January for 24 hours cycle.	124

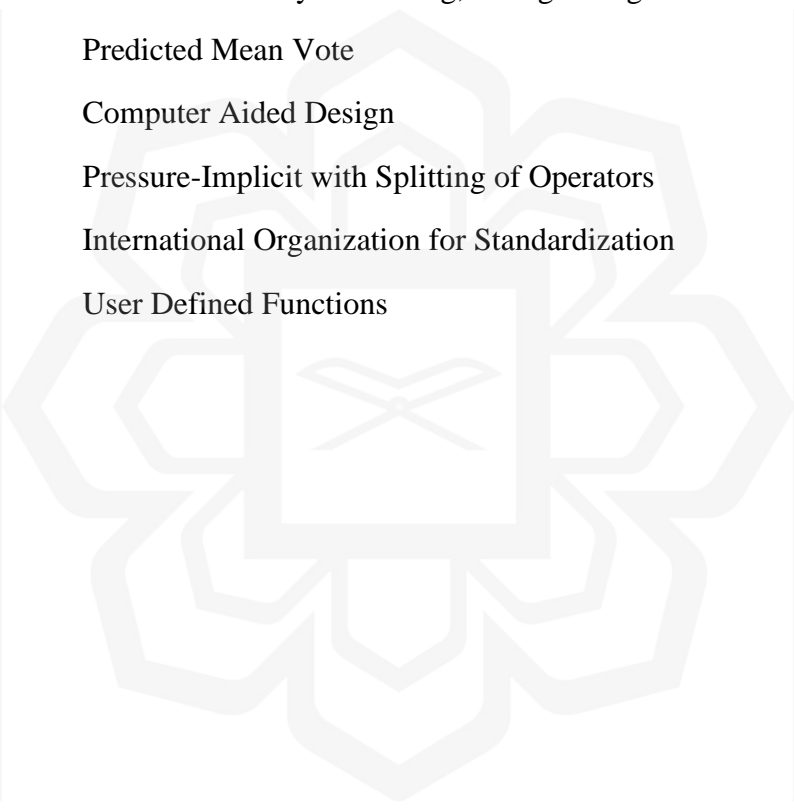
Figure 4.11	Temperature profile for the basement for February at 2.5m/s.	125
Figure 4.12	Temperature profile for the basement for February at 1m/s.	126
Figure 4.13	Temperature profile for the basement for February at 0.5m/s.	126
Figure 4.14	Temperature profile of the basement during February for 24 hours cycle	127
Figure 4.15	Temperature profile for the basement for March at 2.5m/s	128
Figure 4.16	Temperature profile for the basement for March at 1m/s	128
Figure 4.17	Temperature profile for the basement for March at 0.5m/s	129
Figure 4.18	Temperature profile of the basement during March for 24 hours cycle	130
Figure 4.19	Temperature profile for the basement for April at 2.5m/s	131
Figure 4.20	Temperature profile for the basement for April at 1m/s	131
Figure 4.21	Temperature profile for the basement for April at 0.5m/s	132
Figure 4.22	Temperature profile of the basement during April for 24 hours cycle	133
Figure 4.23	Temperature profile for the basement for May at 2.5m/s	134
Figure 4.24	Temperature profile for the basement for May at 1m/s	134
Figure 4.25	Temperature profile for the basement for May at 0.5m/s	135
Figure 4.26	Temperature profile of the basement during May for 24 hours cycle	136
Figure 4.27	Temperature profile for the basement for June at 2.5m/s	137
Figure 4.28	Temperature profile for the basement for June at 1m/s	137
Figure 4.29	Temperature profile for the basement for June at 0.5 m/s	138
Figure 4.30	Temperature profile of the basement during June for 24 hours cycle.	138
Figure 4.31	Temperature profile for the basement for July at 2.5 m/s	139
Figure 4.32	Temperature profile for the basement for July at 1 m/s	140
Figure 4.33	Temperature profile for the basement for July at 0.5 m/s	140

Figure 4.34	Temperature profile of the basement during July for 24 hours cycle.	141
Figure 4.35	Temperature profile for the basement for August at 2.5 m/s	142
Figure 4.36	Temperature profile for the basement for August at 1 m/s	142
Figure 4.37	Temperature profile for the basement for August at 0.5 m/s	143
Figure 4.38	Temperature profile of the basement during August for 24 hours cycle	143
Figure 4.39	Temperature profile for the basement for September at 2.5 m/s	144
Figure 4.40	Temperature profile for the basement for September at 1 m/s	145
Figure 4.41	Temperature profile for the basement for September at 0.5 m/s	145
Figure 4.42	Temperature profile of the basement during September for 24 hours cycle	146
Figure 4.43	Temperature profile for the basement for October at 2.5 m/s	147
Figure 4.44	Temperature profile for the basement for October at 1 m/s	147
Figure 4.45	Temperature profile for the basement for October at 0.5 m/s	148
Figure 4.46	Temperature profile of the basement during October for 24 hours cycle	149
Figure 4.47	Temperature profile for the basement for November at 2.5 m/s	150
Figure 4.48	Temperature profile for the basement for November at 1 m/s	150
Figure 4.49	Temperature profile for the basement for November at 0.5 m/s	151
Figure 4.50	Temperature profile of the basement during November for 24 hours cycle.	152
Figure 4.51	Temperature profile for the basement for December at 2.5 m/s	153
Figure 4.52	Temperature profile for the basement for December at 1 m/s	153
Figure 4.53	Temperature profile for the basement for December at 0.5 m/s	154
Figure 4.54	Temperature profile of the basement during December for 24 hours cycle	155
Figure 4.55	Temperature profile of the cross-sectional thermal mass when 2.5m/s parallel air velocity on the month of June.	157

Figure 4.56	A significant impact of low airspeed towards evaporative effacious when large portion of cool air accumulated and spread throughout the basement.	158
Figure 4.57	Graph showing differences of inlet air temperature with outlet air temperature in terms of air velocity interventions.	159
Figure 4.58	Temperature profile for the basement for June at 2.5m/s	160
Figure 4.59	Temperature profile for the basement for June at 1m/s	160
Figure 4.60	Temperature profile for the basement for June at 0.5 m/s	161
Figure 4.61	Temperature reduction profile of the tested airspeed scenario for 12 months	162
Figure 4.62	Temperature profile for month of June without water elements where air enters the basement at initial velocity of 2.5 m/s.	163
Figure 4.63	Velocity profile for month of June without water elements where air enters the basement at initial velocity of 2.5 m/s.	163
Figure 4.64	The impact of evaporative cooling by waterwall and thermal mass is clearly visible when water is presence in the basement.	164

## LIST OF ABBREVIATIONS

GBI	Green Building Index
SRI	Solar Reflectance Index
UHI	Urban Heat Island Impact
CFD	Computational Fluid Dynamics
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning
PMV	Predicted Mean Vote
CAD	Computer Aided Design
PISO	Pressure-Implicit with Splitting of Operators
ISO	International Organization for Standardization
UDF	User Defined Functions



## LIST OF SYMBOLS

$^{\circ}\text{C}$	Degrees Celsius
K	Degrees Kelvin
Rh	Relative Humidity
$\text{m}^2$	Meter square
m/s	Air velocity (meter per second)
$T_{\text{mrt}}$	Mean Radiant Temperature
TL	Time Lag
k- $\epsilon$	K-epsilon Turbulence Model
$\text{g}_s$	Amount of Evaporated Water per second (kg/s)
$\phi$	Evaporation coefficient
A	Water Surface Area ( $\text{m}^2$ )
$X_s$	Maximum Humidity Ratio of Saturated Air
X	Humidity Ratio Air
$q$	Heat loss ( $\text{Kj}/\text{m}^2$ )
$h_{we}$	Evaporation Heat of Water ( $\text{Kj}/\text{kg}$ )

# CHAPTER ONE

## INTRODUCTION

### 1.1 BACKGROUND OF THE STUDY

It is increasingly realized that sustainability particularly water includes both responses to the climatic and cultural context of a place. There has been a discussion on how these elements of sustainability must eventually imply 'back to basics' and relive lessons from the past approach in terms of environmental characteristics rather than employing 'high technology' add-on features. Hence, there has been a resurging interest in the role of water in urban design and its potential impact on the climatic situation of an area rather than exist only for aesthetic and recreational activities.

Apart from the sustainability agenda, water provides psychological, visual, auditory, and tactile effects, which are primarily perceived by the senses, and affects human psychologically rather than merely visually and physically (Booth, 1989). Hence in terms of aesthetic dimensions, water elements are primarily perceived by the senses as a 'visual element' in urban spaces. However, symbolizing the beginning and the continuity of life it affects human before psychologically rather than visually leading them to it. Except for the directive effect, water elements have also relaxing effects such as visual, acoustic, and provide concentration with tactile integration on the human (Booth, 1989).

Currently, in the arena of sustainable architecture, passive mechanisms are on the rise as it is seen as a cost-effective and value-engineering principles and contribution to sustainability. While passive cooling strategies such as shading, orientation, natural ventilation, and landscape have been researched in-depth, there is a lack of studies in water due to the difficulty of modeling and testing of this element

especially when the water bodies are placed inside a building. According to Yang & Zhao, (2015), previous studies on thermal effects of urban areas under different climatic conditions have tendencies to focus more on pavements and vegetation elements while waterbodies or urban water features are the elements that least studied on.

Passive cooling has been known to be the hallmark of Islamic architecture, particularly to its large building complexes, as many of them are located in hot climate regions. For example, Willmert (2010) usefully discusses and give insight to the environmental rationale and wisdom of typological elements in the Alhambra complex, Granada, Spain from the integral insertion of courtyards, extensions, and projections of patios, to infusion of the complex with optimum dimensions in fountains and pools. He highlights how the demands of the ruling elite had placed a high level of requirement on the environmental conditioning of such complexes, and the ability of the complex to provide this passive attribute to technology during the medieval era, which comfort conditions must be achieved to the highest expectations of the monarch with minimal use of energy.

Study on the environmental characteristics of Islamic heritage structures to gauge the climatic performance, architectural and ecological wisdom is frequently studied in the field of passive low energy architecture. There has been a wide range of studies focuses on a narrative approach to highlight the environmental and architectural ingenuity of Islamic complexes, including narrative socio-cultural studies, while other have utilized more empirical methods of site measurements and the use of computation simulation to analyze and verify the environmental performance of these heritage building complexes.

Previous Islamic civilization that grew under intensely hot regions, have evolved water-based features and achieved a high degree of comfort with minimum use

of renewable energy, as electricity was non-existent at the time. Islamic architectural monuments and complexes have water elements that have become both a spiritual and ecological landmark. Because in Islam, water symbolizes purity and purification, water is an element valued highly due to its purifying and soothing qualifications, and not merely a functional resource. In these complexes, there are endless variations of water elements which are defined as the elements of space different in terms of scale, location, architectural features, material, and design criteria and easily recognized or discernible from several directions (Lynch, 1960).

Islamic architecture, in the word of renowned Malaysian architect, Hijjas Kasturi, is centered on water. Traditionally, in Islamic civilization, water elements have essentially two main purposes; 'aesthetic' and 'functional', hence, the role of water systems may have developed from its essentially agricultural economic base, but it had evolved in complexity and during the height of the empire, it is seen as a form of integrated urban systems which have both socio-ecological and socio-cultural dimensions rather than merely engineered solutions. Water has been part of both outdoors and indoors environment of architecture, and the analysis of indoor and outdoor impact require different tools and computational resources that governed by different equations. Past large building complexes, including its urban and architecture design, constitute a treasure and resource that has yet to be analyzed to the fullest.

As the centuries passed by, modern Islamic states like Malaysia were perceived by the element of water not as the sole cooling medium but as part of aesthetic design intervention. This can be re-look at the design of a few prominent mosques in Malaysia such as Masjid Tuanku Mizan Zainal Abidin, Putrajaya, and Masjid Negara in Kuala Lumpur. Both buildings implement the same scheme of designing the water element surrounding the main prayer area, but Masjid Negara exhibits better thermal