A STUDY ON THERMAL ENVIRONMENTAL PERFORMANCE IN ATRIA IN THE TROPICS WITH SPECIAL REFERENCE TO MALAYSIA

ABD HALID ABDULLAH

HERIOT-WATT UNIVERSITY
SCHOOL OF THE BUILT ENVIRONMENT
MAY 2007

PERPUSTAKAAN UTHM
30000002354270
CN 120 [illegible]

A Study on Thermal Environmental Performance in Atria in the Tropics with Special Reference to Malaysia

by

Abd Halid Abdullah

submitted for the degree of Doctor of Philosophy

Heriot-Watt University

School of the Built Environment

May 2007

This copy of the thesis has been supplied on condition that anyone who consults it is understood to recognize that the copyright rests with its author and that no quotation from the thesis and no information derived from it may be published without the prior written consent of the author or of the University (as may be appropriate).

ABSTRACT

This research investigated the thermal environmental performance of atria in the tropics, with special reference to Malaysia. The main design problems that affect the thermal and energy performance in existing Malaysian atria are overlighting and overheating due to the direct application of western top-lit atrium roof form. As such, this research proposed the side-lit atrium form which aimed at controlling direct sunlight as a way to improve thermal and energy performance of atria in the tropics. Based on the proposed conceptual atrium form, this research examined quantitatively some of the low energy design features and ventilation strategies that can possibly contribute to a better indoor thermal environmental performance of atria in the tropics. The ultimate aim of this research is to propose design principles and guidelines for new low-energy atria in the tropics.

The combined research methods are as follows: developing a conceptual low energy atrium form based on the vernacular design features to be used for computer modelling studies; carrying out field measurement and monitoring on an existing atrium building which provides validation data for dynamic thermal simulation program TAS; modelling exercise on the same monitored building using dynamic thermal modelling to develop confidence in correctly modelling thermal stratification within the multi-level atrium; employing dynamic thermal modelling to model representative atrium forms (i.e. both side-lit and top-lit model) and examine quantitatively the effects of some of the key design parameters (i.e. wall-to-roof void area, roof overhangs, and internal solar blinds) on the thermal comfort and energy performance in atria due to both full natural ventilation and pressurised ventilation; and utilising computational fluid dynamics (CFD) to complement the dynamic thermal simulation results, and to investigate quantitatively the thermal and ventilation performance within the atrium well in response to the changes of design parameters (i.e. varying the inlet to outlet opening area ratio and outlet's arrangement).

The research findings supported the research proposition and demonstrated the effectiveness of the side-lit form as a way to improve the thermal and energy performance with regard to users' thermal comfort in atria in the tropics. The main findings from both dynamic thermal simulation and computational fluid dynamics (CFD) are as follows: full natural ventilation strategy is not viable for Malaysian atria; both sufficiently high wall-to-roof void area and extending high-level internal solar blinds can greatly improve the atrium's thermal performance particularly on occupied levels; sufficiently wide roof overhangs above the clerestory areas of the side-lit atrium form generally improves the thermal and energy performance within the central atrium throughout the year; reasonably comfortable thermal environment on occupied levels of a low-rise atrium can be achieved by only supplying cooler air at low-level with sufficient ventilation rate; sufficiently higher inlet to outlet opening area ratio can improve the thermal performance on the occupied levels; and with equal inlet and outlet opening area, changing the outlet's arrangement (i.e. location and arrangement) would not significantly affect the atrium's thermal performance.

For my parents, beloved wife and children.

ACKNOWLEDGEMENTS

I wish to express my sincere thanks and gratitude to my supervisor, Dr Fan Wang, for his guidance, advice, support, encouragement and help to make this thesis a reality. I am also grateful to the Director of Research, Professor Gareth Pender, for his valuable support and contributions in the preparation of this thesis.

I acknowledge the assistance of students and staff at the Department of Architecture, South China University of Technology, Guangzhou for their willingness to cooperate during the field measurement and monitoring period. In particular I would like to address special thanks to Professor Meng Qinlin and Associate Professor Zhao Lihua for their support and valuable suggestions; and the following students: Zhang Yu, Gao Yunfei, Tu Jianwei, Jin Ling, Wang Zhigang, Pan Yufen, Chen Zhuolun, Hu Shaohua, Liu Yanhua, and Zhau Quan, for their technical support and assistance, without whom the completion of the field measurement would have been highly improbable.

My thanks go to the staff at the School of the Built Environment, Heriot-Watt University. I would especially like to thank Dr Iain MacDougall and Ms Margaret Inglis for providing assistance and technical support during the course of running the simulations using both dynamic thermal software TAS and computational fluid dynamics software PHOENICS in the Resource Room.

I wish to thank the University Tun Hussein Onn Malaysia (UTHM) and the Government of Malaysia for awarding me the scholarship that enables me to do this research.

My special thanks must go to my beloved wife, Rozana Mohd Ali for the support, sacrifice and patience throughout the long period of this research and to my lovely children (Laila Nazneen, Mohd Zulhilmi, Mohd Aiman, Mohd Hariz and Nurin Mastura) for their understanding of not spending enough time with them.

ACADEMIC REGISTRY
Research Thesis Submission

HERIOT
WATT
UNIVERSITY

Name:	ABD HALID ABDULLAH		
School/PGI:	School of the Built Environment		
Version: *(i.e. First, Resubmission, Final)*	Final	Degree Sought:	PhD

Declaration

In accordance with the appropriate regulations I hereby submit my thesis and I declare that:

1) the thesis embodies the results of my own work and has been composed by myself
2) where appropriate, I have made acknowledgement of the work of others and have made reference to work carried out in collaboration with other persons
3) the thesis is the correct version of the thesis for submission*.
4) my thesis for the award referred to, deposited in the Heriot-Watt University Library, should be made available for loan or photocopying, subject to such conditions as the Librarian may require
5) I understand that as a student of the University I am required to abide by the Regulations of the University and to conform to its discipline.

* *Please note that it is the responsibility of the candidate to ensure that the correct version of the thesis is submitted.*

Signature of Candidate:		Date:	03 July 2007

Submission

Submitted By *(name in capitals)*:	
Signature of Individual Submitting:	
Date Submitted:	

For Completion in Academic Registry

Received in the Academic Registry by *(name in capitals)*:			
Method of Submission *(Handed in to Academic Registry; posted through internal/external mail)*:			
Signature:		Date:	

TABLE OF CONTENTS

Abstract i

Dedication iii

Acknowledgements iv

Declaration statement v

Table of Contents vi

List of Tables xii

List of Figures xiv

Glossary of Symbols xx

Published Papers xxv

Chapter 1 : Introduction

1.1 Background 1

1.1.1 Background on Global Pollution 2

1.1.2 Malaysia in General and Its Socio-economic Profile 4

1.1.3 Overview of Malaysia's Current and Future Energy Scenario 5

1.1.4 Current Architectural Practice in Malaysia 8

1.1.5 Issues Concerning Atrium Buildings 9

1.2 Research Problem 13

1.3 Research Objectives 14

1.4 Research Justification and Significance 17

1.5 Research Scope 18

1.6 Structure of the Thesis 19

Chapter 2 : Literature Review

2.1 Introduction 22

2.2 Tropical Climates and Architecture 22

2.2.1 Definition and Areas of Tropical Climate 22

2.2.2 Analysis of Hot and Humid Tropical Climate of Malaysia 23

2.2.3 General Characteristics of the Hot Humid Climate of Peninsular Malaysia 34

2.2.4 The External Climatic Design Data for Kuala Lumpur, Malaysia 36
2.2.5 General Considerations for Hot and Humid Tropical Architecture 38
2.3 Atrium Review 40
2.3.1 Historical Development and Its Evolution 40
2.3.2 The Modern Atrium and Its Definition 42
2.3.3 The Generic Atrium Forms 45
2.3.4 Atrium Buildings in Malaysia 46
2.3.5 Overview of Research Trend in Atria 52
2.4 Thermal Comfort 57
2.4.1 Human Comfort and Thermoregulatory System 57
2.4.2 Factors Affecting Comfort 61
2.4.3 Comfort Equations 62
2.4.4 Comfort Zones 65
2.4.5 Indoor Comfort Criteria for Malaysians 67
2.5 Building Ventilation Systems 69
2.5.1 Critical Parameters in Ventilation System Design 70
2.5.2 Types of Ventilation System 71
2.5.3 Theory for Natural Ventilation by Thermal Buoyancy in Atria 78
2.6 Common Research Methods and Experimental Procedures for Atrium Studies 88
2.6.1 Actual Building Measurement 88
2.6.2 Scale Model Experiments 90
2.6.3 Computer Modelling 92
2.6.4 Combined Methods 94
2.7 Summary 95

Chapter 3 : Research Methodology

3.1 Introduction 97
3.2 Conceptual Atrium Form 98
3.3 Field Measurement 99
3.4 Dynamic Thermal Building Simulation 100

3.4.1 Overview of TAS Applications 101
3.4.2 Justification of TAS 113
3.5 CFD Simulation 114
3.5.1 Overview of CFD Applications 115
3.5.2 Governing Equations 116
3.5.3 Numerical Grid 118
3.5.4 Turbulence Modelling 121
3.5.5 Wall Functions 128
3.5.6 Discretisation Scheme 128
3.6 Summary 130

Chapter 4: Vernacular Architecture as the Basis for the Development of a Conceptual Low-Energy Atrium Form
4.1 Introduction 131
4.2 Vernacular Architecture of Malaysia and Their Main Characteristics 132
4.3 The Validity and Limitations of Using Vernacular Forms and Design Principles 139
4.4 Basic Principles of a Low-Energy Building Design 146
4.5 The Proposed Low Energy Atrium Form for Malaysia 151
4.5.1 Justification of Utilising the Side-lit Linear Atrium Form 154
4.6 Summary 155

Chapter 5 : A Field Study on Indoor Thermal Environment in an Atrium in the Tropics
5.1 Introduction 156
5.2 General Characteristics of Guangzhou Weather 157
5.3 Description of Building and Solar Control Strategy 157
5.4 The Objectives of the Field Study 161
5.5 The Variables Measured and Equipment Used 162
5.5.1 Measurement of Thermal Comfort 162
5.5.2 Measurement of Internal Surface Temperatures 165
5.5.3 Measurement of Radiation Intensity of Internal Surfaces 166
5.5.4 Measurement of Air Temperatures 167
5.6 Calibration of Experimental Equipment 169

5.7 Experimental Procedures 170
5.8 Results and Discussion 171
5.9 Conclusion 175

Chapter 6 : Verification and Validation of the Dynamic Thermal Modelling Software TAS

6.1 Introduction 177
6.2 Description of the 3-D TAS Atrium Model and Simulation 178
  6.2.1 3-D TAS Model 179
  6.2.2 Building Data 182
6.3 Sensitivity Testing of the 3-D TAS Model 185
  6.3.1 Sensitivity Test Analysis 186
6.4 Results and Discussion 192
6.5 Conclusion 197

Chapter 7 : Dynamic Thermal Modelling to Study the Thermal Environmental Performance in Malaysian Atria

7.1 Introduction 200
7.2 General Characteristics of the Tested Atrium Models 201
  7.2.1 The Representative Models 202
  7.2.2 Variations of the Representative Models for Parametrical Studies 202
7.3 The Objectives of the Dynamic Thermal Modelling 204
7.4 Description of the 3D-TAS Atrium Model and Simulations 204
  7.4.1 Fully Naturally Ventilated Simulation 208
  7.4.2 Pressurised Air Ventilation Simulation 210
7.5 Criteria for Assessment of Indoor Thermal Performance and Comfort 216
7.6 Results and Discussion 218
  7.6.1 Fully Naturally Ventilated Simulation 218
  7.6.2 Pressurised Air Ventilation Simulation 228
7.7 Conclusion 234

Chapter 8 : Computational Fluid Dynamics (CFD) Modelling Study of Thermal Environmental Performance in Atria

8.1 Introduction 237
8.2 Criteria for Assessment of Indoor Thermal Performance and Comfort 238
8.3 Development of CFD Atrium Model 239
  8.3.1 Domain 239
  8.3.2 Boundary Conditions 240
  8.3.3 Turbulence Model 243
  8.3.4 Radiation Model 244
  8.3.5 Grid Density 245
  8.3.6 Iteration Number 246
8.4 Parametrical studies 247
  8.4.1 The Effect of Varying Opening Area Ratio on Atrium's Thermal Environmental Performance 247
  8.4.2 The Effect of Outlet's Arrangement on Atrium's Thermal Environmental Performance 250
8.5 Results and Discussion 252
  8.5.1 CFD Atrium Model Tests 253
  8.5.2 Validation of CFD Atrium Models 255
  8.5.3 Parametrical Studies 259
8.6 Conclusion 269

Chapter 9 : Conclusions and Recommendations

9.1 Introduction 271
9.2 Summary of Research Development 271
9.3 Conclusions 273
  9.3.1 Low-Energy Atrium Form for the Hot Humid Tropical Regions 274
  9.3.2 Field Study on Indoor Thermal Environment in an Atrium in the Tropics 275
  9.3.3 Validation of the Dynamic Thermal Modelling Program TAS 277

9.3.4 Dynamic Thermal Modelling of the Representative Atrium Models 279
9.3.5 CFD Modelling of the Representative Atrium Models 282
9.3.6 Other General Considerations 284
9.4 Recommendations for Future Research 285

Appendix A : Equipment for Measurement of Internal Surface Temperature and Radiation Intensity of Internal Surfaces 288

Appendix B : Dynamic Thermal Modelling (TAS program) of the Xihu Yuan Guesthouse, Guangzhou 289

Appendix C : Dynamic Thermal Modelling (TAS program) of the Representative Atrium Models (Side-lit and Top-lit Models) 300

Appendix D : Computational Fluid Dynamics (CFD) Modelling of the Representative Atrium Models (Side-lit and Top-lit Models) 309

Reference 314

LIST OF TABLES

Table 2.1 Summary of comparison of mean daily solar radiation for various stations in Peninsular Malaysia. 25

Table 2.2 Mean daily value of solar radiation for major stations in Peninsular Malaysia. 25

Table 2.3 Average hourly solar radiation for Subang Station in March. 26

Table 2.4 Average number of hours of bright sunshine per month/year. 27

Table 2.5 Mean daily hours of sunshine for five major stations. 27

Table 2.6 Comparison of air temperature for stations in Peninsular Malaysia 29

Table 2.7 Mean daily air temperature for four stations in Peninsular Malaysia. 29

Table 2.8 Comparison of relative humidity for six stations in Peninsular Malaysia. 30

Table 2.9 Comparison of mean daily relative humidity for five stations in Peninsular Malaysia. 30

Table 2.10 Comparison of daily prevailing wind direction. 32

Table 2.11 Relationship of winds, season and rainfall regime. 32

Table 2.12 Comparison of mean annual rainfall amount and highest month. 33

Table 2.13 Comparison of mean daily rainfall amount for five stations in Peninsular Malaysia. 33

Table 2.14 The ASHRAE scale of thermal sensation 63

Table 2.15 Neutral temperature and comfort ranges of subjects in Malaysia. 68

Table 2.16 Approximate ventilation rates requirement. 70

Table 2.17 Measurement techniques and applications. 89

Table 6.1 Net air movement within atrium zones at 1600 hours 189

Table 7.1 Cooling load and supply air flow rate for office zones (Side-lit model). 213

Table 7.2 Cooling load and supply air flow rate for office zones (Top-lit model). 213

Table 7.3 Inter-zone air movement: All floors pressurised (Side-lit model). 214

Table 7.4 Inter-zone air movement: All floors pressurised (Top-lit model). 215

Table 7.5 Inter-zone air movement: Ground floor only pressurised (Side-lit model). 216
Table 7.6 Inter-zone air movement: Ground floor only pressurised (Top-lit model). 216
Table 8.1 The supply airflow rate for each of the low-level inlet openings. 241
Table 8.2 Estimated net heat input, $Q_{S,}$ within the atrium for both representative models at 1400 hours. 242
Table 8.3 The size and location of high-level outlet opening for both representative models due to different opening area ratios. 248
Table 8.4 The z-coordinates at which the average air temperatures were taken at three levels within each of the atrium levels. 253

LIST OF FIGURES

Figure 1.1 Map of Malaysia and South East Asian region. 4
Figure 1.2 Malaysia energy share of total primary energy supply in 2003. 6
Figure 1.3 Malaysia energy consumption in 2003 by sector. 6
Figure 1.4 Malaysia primary energy consumption per dollar of gross domestic product (GDP) between 1980-2000. 7
Figure 1.5 Indoor visual and thermal environmental consequences of a typical top-lit tropical atrium. 14
Figure 1.6 The resultant indoor visual and thermal environment in a side-lit (clerestory windows) atrium in the tropics. 16
Figure 2.1 Tropical regions: humid and dry tropics. 23
Figure 2.2 Potential of climatic controls to flatten the temperature curve from natural conditions. 38
Figure 2.3 Plan and section of House of Ur, Mesopotamia. 41
Figure 2.4 Plan and section of Persian House, showing the use of courtyard and badger. 41
Figure 2.5 Plan and interior perspective of Pension Building, Washington DC. 42
Figure 2.6 Typical guest room plan and section through atrium, Hyatt Regency Hotel, Atlanta. 43
Figure 2.7 Ground floor plan, top floor plan, and section through atrium, The Ford Foundation Headquarters, New York. 44
Figure 2.8 Section through sunspace of Clifton Nurseries by Terry Farrell. 45
Figure 2.9 Generic form of atrium building. 45
Figure 2.10 Plan of the Weld Shopping Mall, Kuala Lumpur showing typical use of the atrium as a space organiser 46
Figure 2.11 Bin Laden Headquarters Building, Jeddah 47
Figure 2.12 The degree of cooling required in an atrium in warm and humid condition 48
Figure 2.13 The importance of orientation in avoiding solar heat gain in tropical area. 50

Figure 2.14 Critical cut-off angle for Malaysia on North and South walls for effective shading design. 50
Figure 2.15 Radiative cooling 51
Figure 2.16 Convective cooling 52
Figure 2.17 Body heat exchange. 58
Figure 2.18 Schematic diagram of the thermoregulatory system in man. 60
Figure 2.19 Predicted Percentage of Dissatisfied (PPD) as a function of Predicted Mean Vote (PMV). 64
Figure 2.20 The Bioclimatic Chart by Olgyay [1963], with an activity level of 1.2 met and clothing insulation of 1.0 in warm climates. 65
Figure 2.21 The Psychrometric Chart marks up as the Building Bioclimatic Chart by Givoni 66
Figure 2.22 Ventilation rates for fresh air control. 71
Figure 2.23 Wind pressure drives cross ventilation. 72
Figure 2.24 A chimney uses the wind to create suction and the stack effect within the building to the air flow. 73
Figure 2.25 Mechanical supply-only ventilation. 74
Figure 2.26 Combined natural ventilation and supply-only mechanical ventilation (Displacement ventilation). 74
Figure 2.27 Mechanical extract-only ventilation. 75
Figure 2.28 Balanced Mechanical System. 76
Figure 2.29 Zonal mixed-mode strategy 77
Figure 2.30 Seasonal mixed-mode. 78
Figure 2.31 Natural ventilation through two openings by thermal buoyancy. 79
Figure 2.32 Pressures, pressure differences and air velocities at the two openings. 84
Figure 3.1 2-D Cartesian grids with non-uniform grid spacing. 119
Figure 3.2 Structured and body-fitted 2-D grid for the simulation of airflow around a person. 119
Figure 3.3 Unstructured grid of the inside surfaces of the 'Reichstag' building, Berlin. 120
Figure 3.4 Hierarchy of turbulence model. 122
Figure 4.1 The traditional Malay house. 133
Figure 4.2 Climatic response in traditional Malay house. 133

Figure 4.3 An open settlement pattern of the traditional Malay houses in rural context. 134
Figure 4.4 Typical traditional Chinese shophouse showing five-foot walkway and jack roof. 136
Figure 4.5 The interior layout of a typical two-storey Chinese shophouse. 137
Figure 4.6 Jack roof and double-tiered roof designed to enhance natural ventilation. 137
Figure 4.7 Vernacular mosque in Malaysia, using double-hipped roof and clerestories for natural lighting and ventilation. 138
Figure 4.8 Schematic drawings of the proposed conceptual atrium form for Malaysia. 152
Figure 5.1 Ground floor plan and cross section of Xihu Yuan Guesthouse. 158
Figure 5.2 The west facing atrium of Xihu Yuan Guesthouse. 159
Figure 5.3 Internal roof blinds in an atrium of Xihu Yuan Guesthouse. 160
Figure 5.4 Water spray on the atrium's glazed roof of Xihu Yuan Guesthouse. 161
Figure 5.5 B & K Thermal Comfort Meter Type 1212. 163
Figure 5.6 Yokogawa Data Logging System DA 100. 167
Figure 5.7 Schematic cross-section showing vertical measuring points (thermocouples position). 168
Figure 5.8 Indoor / Outdoor average air temperature. 171
Figure 5.9 Average vertical radiation intensity and roof surface temperature. 172
Figure 5.10 Average horizontal radiation intensity and roof surface temperature. 173
Figure 5.11 Average internal surface temperatures and Predicted Mean Vote (0.3 clo). 174
Figure 6.1 The 3-D geometric TAS model of Xihu Yuan Guesthouse. 179
Figure 6.2 The ground floor plan of Xihu Yuan Guesthouse in 3D-TAS. 180
Figure 6.3 First floor atrium zones allocation of Xihu Yuan Guesthouse in 3-D TAS. 181
Figure 6.4 Schematic cross-section of the Xihu Yuan Guesthouse showing atrium zones vertically. 181
Figure 6.5 Average air and mean radiant temperatures at 1600 hrs due to the difference solar irradiances. 187
Figure 6.6 Zones air temperature and net inter-zone bulk air movement between the atrium zones at 1600 hours. 190

Figure 6.7 Average measured/predicted air temperatures for hot and overcast day. 192

Figure 6.8 Average measured/predicted air temperatures for hot and clear day. 192

Figure 6.9 Average measured/predicted resultant temperature and roof blinds surface temperature for hot and clear day. 195

Figure 6.10 Average measured/predicted air and mean radiant temperatures at 1400 hrs. 196

Figure 7.1 The representative atrium models. 202

Figure 7.2 Variations of the representative models for parametrical studies. 203

Figure 7.3 The 3-D TAS atrium models. 205

Figure 7.4 Schematic cross-section showing atrium zones for representative models. 206

Figure 7.5 Total daily solar heat gains: Representative models vs. Models without wall-to-roof void. 219

Figure 7.6 Average air temperatures at 1400 hrs due to different sizes of low- and high- level openings (in m^2): Side-lit representative model. 221

Figure 7.7 Average air temperatures at 1400 hrs due to different sizes of low- and high- level openings (in m^2): Top-lit representative model. 221

Figure 7.8 Average air temperatures at 1400 hrs due to different wind speeds: Representative models. 222

Figure 7.9 Average air/mean radiant temperatures at 1400 hrs: Side-lit models with and without wall-to-roof void. 223

Figure 7.10 Average air/mean radiant temperatures at 1400 hrs: Top-lit models with and without wall-to-roof void. 224

Figure 7.11 Seasonal daily solar heat gains: Side-lit models with and without roof overhang. 225

Figure 7.12 Average air/mean radiant temperatures at 1400 hrs: Side-lit models with and without roof overhang. 226

Figure 7.13 Solar heat gains for models with internal solar blinds. 227

Figure 7.14 Average air/mean radiant temperatures at 1400 hrs: Side-lit models with and without internal solar blinds. 228

Figure 7.15 Average air/mean radiant temperatures at 1400 hrs: Top-lit models with and without internal solar blinds. 228

Figure 7.16 Total daily sensible/latent loads: 'all occupied floors pressurised' vs. 'ground floor only pressurised'. 229
Figure 7.17 Average air temperatures on occupied levels due to 'all occupied floors pressurised' ventilation. 230
Figure 7.18 Average air temperatures on occupied levels due to 'ground floor only pressurised' ventilation. 231
Figure 7.19 Average air, mean radian and resultant temperatures at 1400 hrs due to 'all occupied floors pressurised' ventilation. 232
Figure 7.20 Average resultant temperatures during office hours due to 'all occupied floors pressurised' ventilation. 232
Figure 7.21 Average air, mean radiant and resultant temperatures at 1400 hrs due to 'ground floor only pressurised': Representative models. 234
Figure 7.22 Average resultant temperatures during office hours due to 'ground floor only pressurised' ventilation. 234
Figure 8.1 Numerical domains of both representative atrium models. 240
Figure 8.2 Models showing low-level inlet and high-level outlet sizes due to different opening area ratios. 249
Figure 8.3 Models showing outlet's arrangement: side-lit model with horizontal top vent and top-lit model with vertical side vent. 251
Figure 8.4 Average air temperature within the atrium due to different grid densities. 254
Figure 8.5 Average air temperature within the atrium due to different iterations. 255
Figure 8.6 Air and resultant temperature distribution at 1400 hours within the side-lit model. 256
Figure 8.7 Air and resultant temperature distribution at 1400 hours within the top-lit model. 257
Figure 8.8 Predicted average air and resultant temperatures within the atrium at 1400 hours resulting from both TAS and CFD simulations. 258
Figure 8.9 Average air temperature and pressure within the side-lit model due to different opening area ratios. 260
Figure 8.10 Average air temperature and pressure within the top-lit model due to different opening area ratios. 260

Figure 8.11 Vector plot of air velocity for opening area ratio, n=1.0 and the average air velocity within the side-lit model due to different opening area ratios. 261

Figure 8.12 Vector plot of air velocity for opening area ratio, n=1.0 and the average air velocity within the top-lit model due to different opening area ratios. 262

Figure 8.13 Air temperature, PMV and resultant temperature plots within the side-lit model for opening area ratio, n=1.0. 263

Figure 8.14 Air temperature, PMV and resultant temperature plots within the top-lit model for opening area ratio, n=1.0. 264

Figure 8.15 Air temperature plot for model with horizontal top vent and the average air temperature within the side-lit model due to different outlet's arrangement. 266

Figure 8.16 Air velocity vector plot for model with horizontal top vent and the average air velocity within the side-lit model due to different outlet's arrangement. 267

Figure 8.17 Air temperature plot for model with vertical side vent and the average air temperature within the top-lit model due to different outlet's arrangement. 267

Figure 8.18 Air velocity vector plot for model with vertical side vent and the average air velocity within the top-lit model due to different outlet's arrangement. 268

GLOSSARY OF SYMBOLS

A	Effective component surface area (m^2)
A_1	Opening area of inlet (m^2)
A_2	Opening area of outlet (m^2)
A_{c1}	Area of the vena contracta for inlet (m^2)
A_{c2}	Area of the vena contracta for outlet (m^2)
A_{du}	DuBois area: body surface area of the human body (m^2)
A_i	The mean of the internal and external surface areas (m^2)
C_{c1}	Contraction coefficient for inlet
C_{c2}	Contraction coefficient for outlet
C_d	Discharge coefficient
C_{v1}	Air velocity coefficient for inlet
C_{v2}	Air velocity coefficient for outlet
c_p	Specific heat capacity at constant pressure of the fluid (=1010 J/kg.K)
$v_{theo,1}$	Theoretically obtained air velocity for inlet (m/s)
$v_{theo,2}$	Theoretically obtained air velocity for outlet (m/s)
ΔE_{fr2}	Friction loss due to airflow through the outlet (J/kg)
f_{cl}	Ratio of man's surface area while clothed to while nude
g	Gravitational acceleration (=9.82 m/s^2)
G_i	Internal radiant exchange between room surfaces (W/K)
h_c	Convective heat transfer coefficient ($W/m^{2o}K$)
h^{int}	Internal convective heat transfer coefficient (W/m^2K)
h^{ext}	External convective heat transfer coefficient (W/m^2K)
$h^{rad,\mathrm{ext}}$	External radiative heat transfer coefficient (W/m^2K)
$h^{rad,\mathrm{int}}$	Internal radiative heat transfer coefficient (W/m^2K)
H	Vertical distance between the centre of inlet and the centre of outlet (m)
H_1	Vertical distance between the inlet and the neutral pressure plane (m)

H_2	Vertical distance between the outlet and the neutral pressure plane (m)
I_{cl}	Thermal resistance of clothing ($m^{2o}C/W$)
k	Kinetic energy of turbulence (m^2/s^2)
L	Characteristic length of the heat transfer surface (m)
M	Metabolic rate (W/m^2)
$\dot{m}$	Mass flow rate (kg/s)
n	Opening area ratio ($= A_1/A_2$)
p	Radiant proportion
p	Static pressure (N/m^2)
p_{i1}	Indoor pressure at inlet (Pa)
p_{i2}	Indoor pressure at outlet (Pa)
Δp_1	Pressure difference across the inlet (Pa)
p_{o1}	Outdoor pressure at inlet (Pa)
p_{o2}	Outdoor pressure at outlet (Pa)
Δp_2	Pressure difference across the outlet (Pa)
P_a	Water vapour pressure in ambient air (millibar)
P_w	The screen water vapour pressure (millibar)
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied (%)
$q^{cond,\text{int}}$	Internal surface conduction heat flux (W/m^2)
$q^{cond,\text{ext}}$	External surface conduction heat flux (W/m^2)
$q^{conv,\text{int}}$	Internal convective heat flux (W/m^2)
$q^{conv,\text{ext}}$	External convective heat flux (W/m^2)
q^{dir_beam}	Direct normal (beam) solar radian intensity (W/m^2)
$q_{hor}^{dir,\text{ext}}$	Direct solar radiation on the horizontal plane (W/m^2)
q_{env}	Total long-wave incident on the surface from its environment (W/m^2)
q^{ext}	Long-wave radiant flux by the external surface (W/m^2)
q_{hor}^{glob}	The global radiation incident on the horizontal plane (W/m^2)
q_{gnd}	Long-wave incident on the surface from the sky (W/m^2)