

**NUMERICAL SIMULATION FOR THERMAL COMFORT
USING CONDITIONED AIR THROUGH MIXING AND
PERSONALIZED VENTILATION SYSTEMS IN FIELD
ENVIRONMENTAL CHAMBER (FEC)**

By

Eng. Hossam Awad El-Maghraby Abdelaal

**A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the Requirements for the Degree of
MASTER OF SCIENCE
In
MECHANICAL POWER ENGINEERING**

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA – EGYPT**

2014

**NUMERICAL SIMULATION FOR THERMAL COMFORT
USING CONDITIONED AIR THROUGH MIXING AND
PERSONALIZED VENTILATION SYSTEMS IN FIELD
ENVIRONMENTAL CHAMBER (FEC)**

By

Eng. Hossam Awad El-Maghraby Abdelaal

**A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the Requirements for the Degree of
MASTER OF SCIENCE**

**In
MECHANICAL POWER ENGINEERING**

Under Supervision of

**Prof. Dr. Essam E. Khalil Hassan Khalil Dr. Esmail Mohamed Ali El-Bialy
Dr. Omar Ahmed Huzayyin**

**Mechanical Power Engineering Department
Faculty of Engineering
Cairo University**

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA – EGYPT**

2014

**NUMERICAL SIMULATION FOR THERMAL COMFORT
USING CONDITIONED AIR THROUGH MIXING AND
PERSONALIZED VENTILATION SYSTEMS IN FIELD
ENVIRONMENTAL CHAMBER (FEC)**

By

Eng. Hossam Awad El-Maghraby Abdelaal

**A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the Requirements for the Degree of
MASTER OF SCIENCE**

**In
MECHANICAL POWER ENGINEERING**

Approved by the Examining Committee

Prof. Dr. Essam E. Khalil Hassan Khalil

**Thesis Advisor
and Member**

Prof. Dr. Mahmoud Ahmed Fouad

Member

Prof. Dr. Osama Ezzat Abdel-Latif

Member

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA – EGYPT**

2014

Engineer: Hossam Awad El-Maghraby Abdelaal
Date of Birth: 01/11/1989
Nationality: Egyptian
E-mail: hossam.elmaghraby@eng.cu.edu.eg
Phone: 00201226703983
Address: 20 Fakhry El-Daly St, Faisal, Giza, Egypt
Registration Date: 01/10/2011
Awarding Date: / /
Degree: Master of Science
Department: Mechanical Power Engineering



Supervisors: Prof. Dr. Essam E. Khalil Hassan Khalil
Dr. Esmail Mohamed Ali El-Bialy
Dr. Omar Ahmed Huzayyin

Examiners: Prof. Dr. Essam E. Khalil Hassan Khalil
Prof. Dr. Mahmoud Ahmed Fouad
Prof. Dr. Osama Ezzat Abdel-Latif (Benha University)

Title of Thesis: NUMERICAL SIMULATION FOR THERMAL COMFORT
USING CONDITIONED AIR THROUGH MIXING AND
PERSONALIZED VENTILATION SYSTEMS IN FIELD
ENVIRONMENTAL CHAMBER (FEC)

Key Words: Conditioned Air, Personalized Ventilation, Mixing Ventilation, Thermal Comfort, FEC, CFD

Summary:

Thermal comfort within a Field Environmental Chamber (FEC) office mockup was numerically simulated throughout the current study. The goal of this research was to determine the best scenario to provide conditioned supply of air and distribute it inside an office room by using Mixing Ventilation (MV) and Personalized Ventilation (PV) systems to create the best status of thermal comfort for a sitting occupant who is typing in front of a computer screen. Computational Fluid Dynamics (CFD) method was used and specifically ANSYS FLUENT 14.0 commercial package software to compare the thermal comfort conditions for the occupant with different strategies of air distribution with various flow rates either being used solely or concurrently. Thermal comfort mathematical indices like the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) were implemented in the software and their contours were shown to define the thermal comfort status more precisely. It was concluded that using PV systems to maintain thermal comfort conditions for a working office occupant can be very effective and an attractive solution for designers to consider in situations similar to the study.

ACKNOWLEDGMENT

In the beginning, I would like to thank The Almighty and Great ALLAH for his help, generous giving to me and for his guidance and reconcile throughout this work and my whole life.

I hereby would like to express my deep gratitude and thanks to Prof. Essam E. Khalil, Dr. Esmail M. A. El-Bialy and Dr. Omar A. Huzayyin for their support, continuous encouragement and distinctive supervision throughout the course of this work. They helped providing me with valuable advice and up to date technical references that were of great help in the present work. I am grateful to them, and to all my respectful professors, for mentoring me throughout my undergraduate and graduate study.

I would like to extend my gratitude to Dr. Waleed A. Abdelmaksoud for his valuable suggestions and noteworthy discussions and for supplying me with some of his publications. I would like to thank Eng. Fawzy Abd El Aziz and Eng. Ahmed Hossam Zaki as well for their great help in software technical issues, and Eng. Sherif Ibrahim for providing me with helpful research papers. Thanks are also extended to my friends and colleagues in Mechanical Power Engineering department for their encouragement and support.

Finally, I would like to thank my family for their great and continuous help and support they provided me to finish this work in a suitable form and my fiancée for her love and care.

TABLE OF CONTENTS

ACKNOWLEDGMENT	v
TABLE OF CONTENTS	vi
LIST OF TABLES	x
LIST OF FIGURES	xi
NOMENCLATURE	xxiii
Greek Letters	xxiv
Superscripts and Subscripts	xxv
Abbreviations	xxv
ABSTRACT	xxvii
1. INTRODUCTION	1
1.1 General.....	1
1.2 Factors Influencing Thermal Comfort of Occupants.....	1
1.3 Thermal Comfort Models	2
1.3.1 Static Comfort Model: PMV/PPD	2
1.3.2 Adaptive Comfort Model	3
1.4 Ventilation in Offices	4
1.5 Types of Ventilation	4
1.5.1 Mixing Ventilation	4
1.5.2 Personalized Ventilation	5
1.6 Air Exchange Rate	7
1.7 Computational Fluid Dynamics (CFD)	8

1.8 Present Work	8
2. LITERATURE REVIEW	9
2.1. Personalized Ventilation	9
2.2. Mixing Ventilation	27
2.3. Using Personalized Ventilation and/or Mixing Ventilation for Thermal Comfort within an Office Room	40
3. GOVERNING EQUATIONS	48
3.1 Introduction	48
3.2 Mass Conservation Equation (Continuity Eqn.)	48
3.3 Momentum Conservation Equation	49
3.4 Energy Conservation Equation	49
3.5 Species Transport Equation	50
3.6 Turbulence Modeling Equations	51
3.6.1 Standard k- ϵ Model	52
3.6.2 RNG k- ϵ Model	53
3.6.3 Realizable k- ϵ Model	56
3.6.4 Definitions Applicable to k- ϵ Models	57
3.6.4.1 Modeling Turbulent Production in k- ϵ Models	57
3.6.4.2 Effect of Buoyancy on Turbulence in k- ϵ Models	58
3.6.4.3 Effect of Compressibility on Turbulence in k- ϵ Models	58
3.6.5 Wall Functions	59
3.6.5.1 Standard Wall Functions.....	60
3.6.5.1.1 Momentum	60
3.6.5.1.2 Energy	61
3.6.5.1.3 Species	62

3.6.5.1.4 Turbulence	62
3.7 PMV/PPD Comfort Model	63
4. GRID SENSITIVITY ANALYSIS AND VALIDATION	64
4.1 Present Case Study	64
4.2 Grid Sensitivity Analysis	65
4.3 Validation	69
4.3.1 Twin-Jet Impingement Model	69
4.3.2 Experimental Measurements in FEC	73
5. RESULTS AND DISCUSSION	78
5.1 New Features in the Present Model	78
5.1.1 Occupant Boundary Condition	78
5.1.2 Computer Hardware Boundary Conditions	78
5.1.3 Occupant Exhalation Boundary Conditions	79
5.2 Present Model Layout	79
5.3 Case Studies	81
5.4 The Effect of Mixing Ventilation Flow Rate (ACH)	85
5.4.1 Case 1 (6 ACH)	86
5.4.2 Case 2 (9 ACH)	93
5.4.3 Case 3 (12 ACH)	100
5.4.4 Case 4 (15 ACH)	107
5.4.5 Overview	114
5.5 The Effect of Personalized Ventilation Flow Rate (L/s)	114
5.5.1 Case 5 (1 L/s per ATD)	116
5.5.2 Case 6 (1.5 L/s per ATD)	122
5.5.3 Case 7 (2 L/s per ATD)	129

5.5.4 Case 8 (2.5 L/s per ATD)	135
5.5.5 Case 9 (3 L/s per ATD)	142
5.5.6 Case 10 (4 L/s per ATD)	148
5.5.7 Overview	154
5.6 The Effect of Combined MV and PV Flow Rates	154
5.6.1 Case 11 (6 ACH & 3 L/s per ATD)	155
5.6.2 Case 12 (9 ACH & 2.5 L/s per ATD)	162
5.6.3 Case 13 (12 ACH & 2 L/s per ATD)	168
5.6.4 Case 14 (15 ACH & 1.5 L/s per ATD)	175
5.6.5 Overview	181
5.7 The Effect of Changing the Exhaust Grills Locations	182
5.7.1 Case 15 (6 ACH with wall mounted exhaust grills)	183
5.7.2 Case 16 (9 ACH with wall mounted exhaust grills)	186
5.7.3 Case 17 (12 ACH with wall mounted exhaust grills)	189
5.7.4 Case 18 (15 ACH with wall mounted exhaust grills)	191
5.7.5 Case 19 (6 ACH & 3 L/s with wall mounted exhaust grills)	193
5.7.6 Case 20 (9 ACH & 2.5 L/s with wall mounted exhaust grills)	195
5.7.7 Case 21 (12 ACH & 2 L/s with wall mounted exhaust grills)	198
5.7.8 Case 22 (15 ACH & 1.5 L/s with wall mounted exhaust grills)	200
5.7.9 Overview	202
5.8 Cases with Best Thermal Comfort Conditions	202
 6. CONCLUSIONS AND FUTURE WORK RECOMMENDATIONS	 204
6.1 Conclusions	204
6.2 Recommendations for Future Work	206
 REFERENCES	 207
APPENDIX	211

LIST OF TABLES

Table 4.1: Comparison between numerical data of RKE model and experimental data of air velocity (m/s) at positions 1 and 2 at 6 ACH.....	77
Table 4.2: Comparison between numerical data of RKE model and experimental data of air velocity (m/s) at positions 1 and 2 at 12 ACH.....	77
Table 5.1: All cases studied in the current research.....	81
Table 5.2: Case studies 1, 2, 3 and 4 to study the effect of MV ACH.....	86
Table 5.3: Case studies from 5 to 10 to study the effect of PV flow rate.....	115
Table 5.4: Case studies 11 to 14 to investigate the effect of combined MV and PV flow rates.....	155
Table 5.5: Case studies 15 to 22 to investigate the effect of changing the locations of exhaust grills.....	183

LIST OF FIGURES

Figure 1.1: Fanger's PMV seven point scale	5
Figure 1.2: Acceptable operative temperature ranges for naturally conditioned spaces ...	5
Figure 1.3: Mixing ventilation within a space	7
Figure 1.4: Personalized ventilation in office	8
Figure 1.5: Personalized ventilation desktop air terminal devices	8
Figure 2.1: Examples of tested air supply terminal devices (ATDs)	12
Figure 2.2: The ventilation effectiveness obtained with the tested ATDs as a function of the flow rate of personalized air under isothermal conditions	13
Figure 2.3: Air conditioning and air distribution in field environmental chamber	14
Figure 2.4: Ductless PV system.....	15
Figure 2.5: Distribution of normalized concentration obtained at location I; the comparison is made for RF (DV alone) and two cases with different combinations of personalized airflows under two displacement rates (60 and 80 L/s)	16
Figure 2.6: Walking scenarios	17
Figure 2.7: Thermal mannequin in displacement room	18
Figure 2.8: Airflow velocity (m/s) contours in the ventilated room with personalized airflow of 1.0 L/s	18
Figure 2.9: A ventilation seat with an adjustable personalized air supply nozzle	19
Figure 2.10: FEC layout	20
Figure 2.11: Desk mounted PV	20
Figure 2.12: Photo of test room showing a PV duct serving the micro-environment surrounding an occupant	20
Figure 2.13: The simulated HVAC system in an office	22
Figure 2.14: Field Environmental Chamber (FEC)	23
Figure 2.15: Geometry applied in Gambit 2.4	23
Figure 2.16: Office mock-up plan	24

Figure 2.17: Details of the positioning of the round movable panel and the vertical desk grille	25
Figure 2.18: FEC with instruments at a single workstation	26
Figure 2.19: The experimental set-up at workstation	27
Figure 2.20: Configuration of the simulated office	28
Figure 2.21: Mixing ventilation air distribution elements	29
Figure 2.22: Schematic of the two ventilated cases	30
Figure 2.23: Schematic of the used test facility	31
Figure 2.24: (a) The geometry of the full-scale test room, (b) Distribution of measurement points for contours of concentrations in the center plane of the test room	32
Figure 2.25: Detailed floor plans of the office building being studied.....	33
Figure 2.26: Typical rooms studied, (a) an office, (b) a classroom, (c) a retail shop, (d) a workshop	35
Figure 2.27: The used model test room, (a) schematic of the model test room and the ventilation scheme, (b) Photo of the model test room	36
Figure 2.28: An example of a mesh generated by VortexIn [®]	37
Figure 2.29: Side view of the test chamber, including air flow	38
Figure 2.30: Schematic diagram for the apparatus with a distributed heating source and ventilation holes on the side of the tank	39
Figure 2.31: Schematic diagram for the apparatus with a localized source of buoyancy and ventilation holes on the side and base of the tank	40
Figure 2.32: Spreading of tracer gas near the mannequins being both the heat and tracer gas source, with displacement flow and mixing flow	41
Figure 2.33: Cross-section and construction of the wall of the test chamber	41
Figure 2.34: 3-D view of two cubicles in the modeled office	43
Figure 2.35: South façade view of ED70 building	45
Figure 2.36: Office rooms analyzed in ED70 building (shaded in gray)	45
Figure 2.37: (a) Frontal and top views of the proposed ceiling diffuser and (b) computational domain	46
Figure 2.38: Graphical overview of experimental cases	48

Figure 2.39: Floor plan for the test room; the orange dots indicate the measurement stands and the gray hatched surfaces represent the plenum boxes	49
Figure 4.1: (a) FEC top view without office or mannequin [6], (b) FEC isometric view on ANSYS 14.0 after locating office and mannequin in the middle of the room.	66
Figure 4.2: Views for the generated grid, (a) front view, (b) side view	66
Figure 4.3: Comparing velocity distribution over FEC length using different mesh sizes..	67
Figure 4.4: Comparing temperature distribution over FEC length using different mesh sizes.....	67
Figure 4.5: Comparing relative humidity (RH) distribution over FEC length using different mesh sizes	68
Figure 4.6: Twin-jet impingement model geometry and setup	69
Figure 4.7: Experimental measurements of twin-jet model at four different heights	70
Figure 4.8: Simulation results of twin-jet normalized vertical velocity at $y/D_j=-1.86$	71
Figure 4.9: Simulation results of twin-jet normalized vertical velocity at $y/D_j=-5.57$	71
Figure 4.10: Simulation results of twin-jet normalized vertical velocity at $y/D_j=-9.29$...	72
Figure 4.11: Simulation results of twin-jet normalized vertical velocity at $y/D_j=-12$	72
Figure 4.12: (a) Positions of transducers and mannequin within FEC, (b) Omnidirectional velocity transducer probes	73
Figure 4.13: Scaled residuals in CFD simulation of the 12 ACH case with RKE model	74
Figure 4.14: Comparison of numerical results with experimental measurements in FEC at 6 ACH; (a) At position 1, (b) At position 2	75
Figure 4.15: Comparison of numerical results with experimental measurements in FEC at 6 ACH; (a) At position 1, (b) At position 2	76
Figure 5.1: Mean skin temperature as a function of the activity level presented by metabolic rate	78
Figure 5.2: Layout of the final model of the office room	80
Figure 5.3: Position of sectional plane A-A within the office room model	83
Figure 5.4: Position of sectional plane B-B within the office room model	83
Figure 5.5: Position of sectional plane C-C within the office room model	84
Figure 5.6: Position of sectional plane D-D within the office room model	84

Figure 5.7: Pathlines of air from ceiling MV system at 6 ACH colored by air velocity magnitude	85
Figure 5.8: Contours of air velocity magnitude in planes C-C and D-D at the centers of the supply vents in case 1	87
Figure 5.9: Contours of air velocity magnitude in plane A-A within the office room in case 1	88
Figure 5.10: Contours of air velocity magnitude in plane B-B within the office room in case 1	88
Figure 5.11: Contours of air temperature in plane A-A within the office room in case 1	89
Figure 5.12: Contours of air temperature in plane B-B within the office room in case 1	89
Figure 5.13: Contours of PMV in plane A-A within the office room in case 1	90
Figure 5.14: Contours of PMV in plane B-B within the office room in case 1	90
Figure 5.15: Contours of PPD in plane A-A within the office room in case 1	91
Figure 5.16: Contours of PPD in plane B-B within the office room in case 1	91
Figure 5.17: Contours of relative humidity in plane A-A within the office room in case 1	92
Figure 5.18: Contours of relative humidity in plane B-B within the office room in case 1	92
Figure 5.19: Contours of air velocity magnitude in planes C-C and D-D at the centers of the supply vents in case 2	94
Figure 5.20: Contours of air velocity magnitude in plane A-A within the office room in case 2	95
Figure 5.21: Contours of air velocity magnitude in plane B-B within the office room in case 2	95
Figure 5.22: Contours of air temperature in plane A-A within the office room in case 2	96
Figure 5.23: Contours of air temperature in plane B-B within the office room in case 2	96
Figure 5.24: Contours of PMV in plane A-A within the office room in case 2	97

Figure 5.25: Contours of PMV in plane B-B within the office room in case 2	97
Figure 5.26: Contours of PPD in plane A-A within the office room in case 2	98
Figure 5.27: Contours of PPD in plane B-B within the office room in case 2	98
Figure 5.28: Contours of relative humidity in plane A-A within the office room in case 2	99
Figure 5.29: Contours of relative humidity in plane B-B within the office room in case 2	99
Figure 5.30: Contours of air velocity magnitude in planes C-C and D-D at the centers of the supply vents in case 3	101
Figure 5.31: Contours of air velocity magnitude in plane A-A within the office room in case 3	102
Figure 5.32: Contours of air velocity magnitude in plane B-B within the office room in case 3	102
Figure 5.33: Contours of air temperature in plane A-A within the office room in case 3	103
Figure 5.34: Contours of air temperature in plane B-B within the office room in case 3	103
Figure 5.35: Contours of PMV in plane A-A within the office room in case 3	104
Figure 5.36: Contours of PMV in plane B-B within the office room in case 3	104
Figure 5.37: Contours of PPD in plane A-A within the office room in case 3	105
Figure 5.38: Contours of PPD in plane B-B within the office room in case 3	105
Figure 5.39: Contours of relative humidity in plane A-A within the office room in case 3	106
Figure 5.40: Contours of relative humidity in plane B-B within the office room in case 3	106
Figure 5.41: Contours of air velocity magnitude in planes C-C and D-D at the centers of the supply vents in case 4	108
Figure 5.42: Contours of air velocity magnitude in plane A-A within the office room in case 4	109
Figure 5.43: Contours of air velocity magnitude in plane B-B within the office room in case 4	109