

NUMERICAL INVESTIGATIONS OF FLOW PATTERNS AND THERMAL COMFORT IN HEAVY TRUCK CABIN

By

Eng. Ahmed Fathy Ibrahim Omran

**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 INVESTIGATIONS OF FLOW PATTERNS AND THERMAL COMFORT IN HEAVY TRUCK CABIN

By

Eng. Ahmed Fathy Ibrahim Omran

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

**Prof. Dr. Ahmed A. Medhat Ahmed
Professor at Housing and Building
National Research Center**

**Dr. Esamil M. ElBialy
Mechanical Power Engineering Department
Faculty of Engineering Cairo University**

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2014**

NUMERICAL INVESTIGATIONS OF FLOW PATTERNS AND THERMAL COMFORT IN HEAVY TRUCK CABIN

By

Eng. Ahmed Fathy Ibrahim Omran

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

**In
MECHANICAL POWER ENGINEERING**

Approved by the Examining Committee

Prof. Dr. Essam E. Khalil Hassan Khalil

Mechanical Power Department - Faculty Of Engineering – Cairo University

(Thesis Advisor
and Member)

Prof. Dr. Mahmoud Ahmed Mahmoud Fouad

Mechanical Power Department - Faculty Of Engineering – Cairo University

(Member)

Prof. Dr. Osama Ezzat Abdel Latif (Member)

Mechanical Power Department - Faculty Of Engineering – Banha University

(Member)

**FACULTY OF ENGINEERING, CAIROUNIVERSITY
GIZA, EGYPT**

2014

Engineer: Ahmed Fathy Ibrahim Omran
Date of Birth : 02 / 12 / 1985
Nationality : Egyptian
E-mail : eng_omran1985@yahoo.com
Phone. : 01129347292 - 01200672006
Address : 82 Sakr Korish – Maadi - Cairo
Registration Date : 01 / 10 / 2012
Awarding Date : / /
Degree : Master of science
Department : Mechanical Power Engineering



Supervisors : Prof. Dr. **Essam E. Khalil Hassan Khalil**
Prof.Dr. **Ahmed Ahmed Medhat**
Dr. **Ismael Mohamed El Bialy**

Examiners : Prof. Dr. **Essam E. Khalil Hassan Khalil**
Prof. Dr. **Mahmoud Ahmed Fouad**
Prof. Dr. **Osama Ezzat Abdel-lattif** (Shoubra faculty of engineering- Benha University)

Title of Thesis: Numerical Investigation Of Flow Patterns And Thermal Comfort In Heavy Truck

Key Words:

(Thermal Comfort; Truck Cabin; Transient Simulation; Transportation)

Summary:

Thermal comfort in heavy truck cabins is a prime concern for designers, owners and passengers. Interior climate is one of the main comfort factors during a trip. Besides, it is also very important for interior safety because air temperature, air velocity and humidity affect the driver's well-being, concern and alertness. Air conditioning and ventilation system is also responsible for providing a well occupied environment for both the driver and the passenger. Recently, there has been a major development in the area of HVAC systems using thermal comfort to insure that the passengers are comfortable staying in the truck cabin. More investigations of the design parameters space is conducted to bring the final design closer to the optimum.

fACKNOWLEDGMENT

Firstly, I would like to thank Almighty ALLAH, whom I owe everything, for His generousness and support through all my life.

The author gratefully acknowledges Prof. Essam E. Khalil for his sincere and thoughtful guidance and assistance throughout the research undertaken. For all their valuable comments added to this research, many thanks are due to Prof. Osama Abdel Latif, Prof. Mahmoud Fouad and Prof. Ahmed Medhat as members of the examining committee.

Thanks are due to Dr. Esmail M. Elbialy and Eng. Osama Abdel Khalek for their support. I am very grateful to my wife Dr. Maha Magrabi and my father Mr. Fathy Omran for their support, understanding and encouragement as faithful companions.

I extend my gratitude to my dear managers and colleagues in Arab Contractors – Road Sector for their great support in both work and study through the last five years.

ACKNOWLEDGMENT

Firstly, I would like to thank Almighty ALLAH, whom I owe everything, for His generousness and support through all my life.

The author gratefully acknowledges Prof. Essam E. Khalil for his sincere and thoughtful guidance and assistance throughout the research undertaken. For all their valuable comments added to this research, many thanks are due to Prof. Osama Abdel Latif, Prof. Mahmoud Fouad and Prof. Ahmed Medhat as members of the examining committee.

Thanks are due to Dr. Esmail M. Elbialy and Eng. Osama Abdel Khalek for their support. I am very grateful to my wife Dr. Maha Magrabi and my father Mr. Fathy Omran for their support, understanding and encouragement as faithful companions.

I extend my gratitude to my dear managers and colleagues in Arab Contractors – Road Sector for their great support in both work and study through the last five years.

TABLE OF CONTENTS

	Page
ACKNOWLEDGMENT.....	i
TABLE OF CONTENTS.....	ii
LIST OF TABLES.....	v
LIST OF FIGURES	vi
NOMENCLATURE	ix
ABBRIVIATIONS	xiii
ABSTRACT.....	xiv

1. Introduction	1
1.1. General.....	1
1.2. Importance of indoor Air Quality.....	2
1.3. Factors That Affect Passenger Thermal Comfort.....	2
1.3.1. Air Temperature.....	2
1.3.2. Air Velocity	2
1.3.3. Mean Radiant Temperature	2
1.3.4. Relative Humidity	2
1.3.5. Human Activity level and Clothing Insulation	3
1.3.6. Metabolic Rat.....	3
1.4. Automotive Air Conditioning.....	4
1.5. Computational Fluid Dynamics	5
1.6. Objective of the Study	7
1.7. Outline of the Thesis	7

2.	LITERATURE REVIEW	8
2.1.	Virtual manikins and CFD in research	8
2.2.	Review of Previous Cabin Models	11
2.3.	Detailed Cases	12
2.3.1.	Case Study 1	12
2.3.2.	Case Study 2	19
3.	Governing Equations	24
3.1.	Introduction	24
3.1.1.	Computational Fluid Dynamics	24
3.1.2.	Fluid element and properties	25
3.2.	Conservation Equations	25
3.2.1.	Continuity equation	26
3.2.2.	The Momentum Equation	26
3.2.3.	Energy equation	28
3.3.	Turbulence model	31
3.3.1.	Introduction	31
3.3.2.	Predicting the turbulent viscosity	32
3.4.	Setting boundary conditions	44
3.5.	Comparison of RANS turbulence models	45
4.	Mathematical Model	46
4.1.	Introduction	46
4.2.	Model Assumptions	46
4.3.	Detailed Description of the Validated Case	47
4.4.	Measurements	47
4.4.1.	The Hot Wire anemometer	48
4.4.2.	Thermocouple Type J	48
4.5.	The Experimental steps	49
4.6.	Experimental Results	49
4.7.	Mesh Generation	50
4.8.	Grid Independence	50
4.9.	Results.....	52
4.9.1.	Steady-State Condition Results	52
4.9.1.1.	Case 1 Steady state	52
4.9.1.2.	Case 2 Steady state	57
4.9.2.	Analysis of the steady – state cases	61

4.9.3. Transient condition Results	62
4.9.3.1. Case 3 Transient	63
4.9.3.2. Case 4 Transient	67
4.9.3.3. Case 5 Transient	71
4.9.3.4. Case 6 Transient	75
4.10. Summary of the results	79
 5. CONCLUSIONS AND SUGGESTED FUTURE WORK	80
5.1. INTRODUCTION	80
5.2. Conclusions of Present Work.....	81
5.3. Recommendations for Future Work.....	81
 References	82

List of Tables

	Page
Table 1-1 Weight factor values at different air velocities values	4
Table 1-2 Comparison between experiments and simulations	7
Table1-2 A summary of the virtual thermal manikin methods	14
Table 2.2 Heat loss data (W/m ²) from a selection of manikin segments	19
Table 2.2 Measured air velocities and temperatures	19
Table 3.1 Comparison of RANS turbulence models	54
Table 4.1 Summery of the resulted cases	79

List of Figures

Figure	Description	Page
1.1	Typical Automotive Air Conditioning System	5
2.1	MANIKIN2 inside the cabin simulator exposed to the artificial sun	17
2.2	Schematic drawing of the cabin simulator	18
2.3	The geometry of the virtual cabin	18
2.4	Temperature patterns in the cabin for the case with and without sun	20
2.5	The flow patterns in the cabin shown as velocity vectors	21
2.6	Typical flow lines released from the sensors	21
2.7	Equivalent temperatures vs. body parts	22
2.8	Outline of the studied system: portion of the touring bus cabin	23
2.9	Numerical grid adopted for computations	24
2.10	Iso-value surfaces of velocity close to the inlet slots	25
2.11	Motion field of air in a transversal vertical section of the cabin	25
2.12	Velocity distribution in a horizontal section of the cabin	26
2.13	Streamlines of the vorticity function	27
2.14	Temperature field at solid-fluid interfaces	27
2.15	Thermal field in a transversal section of the cabin	28
3.1	Fluid element for conservation laws	30
3.2	Mass fluxes entering and leaving an element	32
3.3	Shear stress on the fluid element	33
3.4	Forces in the x-direction	34
3.5	Work done by surface stresses in x-direction	35
3.6	Energy flux due to heat conduction	36
4.1	Model of the Cabin with Driver and passenger	47
4.2	Typical Hotwire arrangements	48
4.3	Meshing of the modeled cabin with 2.1 million	50
4.4	Static temperature of the driver face with different No. of cells	50
4.6	Convergence of scaled residuals with 1.8 million elements	51
4.7	Convergence of scaled residuals with 2.1 million elements	51
4.8	Scaled residuals for case 1 steady – state condition	52
4.9	Convergence history of velocity magnitude for case 1	53
4.10	Convergence history of static temperature case 1	53
4.11	Contours of static temperature on plane $z/H=0$ case 1	54
4.12	Contours of static temperature on plane $z/H=0.8$ case 1	54
4.13	Contours of static temperature on plane $z/H=1$ case 1	55
4.14	Contours of velocity magnitude on plane $z/H=0$ case 1	55

4.15 Contours of velocity magnitude on plane $z/H=0.8$ case 1	56
4.16 Contours of velocity magnitude on plane $z/H=1$ case 1	56
4.17 Scaled residuals for case 2 steady – state conditions	57
4.18 Convergence history of velocity magnitude for case 2	57
4.19 Convergence history of static temperature case 2	58
4.20 Contours of static temperature on plane $z/H=0$ case 2	58
4.21 Contours of static temperature on plane $z/H=0.8$ case 2	59
4.22 Contours of static temperature on plane $z/H=1$ case 2	59
4.23 Contours of velocity magnitude on plane $z/H=0$ case 2	60
4.24 Contours of velocity magnitude on plane $z/H=0.8$ case 2	60
4.25 Contours of velocity magnitude on plane $z/H=1$ case 2	61
4.26 Scaled residuals for Case 3 Transient condition	63
4.27 Convergence history of static temperature Case 3	63
4.28 Contours of static temperature $z/H=0$ Case 3	64
4.29 Contours of static temperature $z/H=0.8$ Case 3	64
4.30 Contours of static temperature $z/H=1$ Case 3	65
4.31 Contours of velocity magnitude on plan $z/H=0$ Case3	65
4.32 Contours of velocity magnitude on plan $z/H=0.8$ Case3	66
4.33 Contours of velocity magnitude on plan $z/H=1$ Case3	66
4.34 Scaled residuals for Case 4 Transient Condition	67
4.35 Convergence history of static temperature Case 4	67
4.36 Contours of static temperature on plan $z/H=0$ Case 4	68
4.37 Contours of static temperature on plan $z/H=0.8$ Case 4	68
4.38 Contours of static temperature on plan $z/H=1$ Case 4	69
4.39 Contours of velocity magnitude at plane $z/H=0$ Case 4	69
4.40 Contours of velocity magnitude at plane $z/H=0.8$ Case 4	70
4.41 Contours of velocity magnitude at plane $z/H=1$ Case 4	70
4.42 Scaled residuals of Case5 Transient Condition	71
4.43 Convergence history of static temperature Case 5	71
4.44 Contours of static temperature of plane $z/H=0$ Case 5	72
4.45 Contours of static temperature of plane $z/H=0.8$ Case 5	72
4.46 Contours of static temperature of plane $z/H=1$. Case 5	73
4.47 Contours of velocity magnitude at plane $z/H=0$ Case 5	73
4.48 Contours of velocity magnitude at plane $z/H=0.8$ Case 5	74
4.49 Contours of velocity magnitude at plane $z/H=1$ Case 5	74

4.50 Scaled residuals of Case 6 Transient Condition	75
4.51 Convergence history of static temperature Case 6	75
4.52 Contours of static temperature on plane $z/H=0$ Case 6	76
4.53 Contours of static temperature on plane $z/H=0.8$ Case 6	76
4.54 Contours of static temperature on plane $z/H=1$ Case 6	77
4.55 Contours of velocity magnitude on plane $z/H=0$ Case 6	77
4.56 Contours of velocity magnitude on plane $z/H=0.8$ Case 6	78
4.57 Contours of velocity magnitude on plane $z/H=1$ Case 6	78

NOMENECLATURE

Symbol	Quantity
Br	Brinkman number, $Br = \frac{\mu U_e^2}{k \Delta T}$
C	Constant
C_p	Constant pressure specific heat, kJ/kg.K
d	Distance, m
D_{im}	diffusion coefficient for species i in mixture m
D	Fluid Domain
E	Total energy of a fluid particle, J
ϵ	Dimension Less term describing the turbulent dissipation rate, ϵ
\vec{F}	External body forces, N
g	Gravitational acceleration, m/s ²
G	Filter function
G_b	Generation of turbulent kinetic energy, k , due to boyancy
G_k	Turbulence kinetic energy production
Gr	Grashohf number, $Gr_L = \frac{g \beta (T_s - T_\infty) L^3}{\nu^2}$
h	Enthalpy, kJ/kg
h_j^0	enthalpy of formation of species j
H	Height, m
I	Unit tensor
I	Fluctuation intensity
\vec{J}_j	Diffusion flux of species j

k	Turbulent Kinetic energy, m^2/s^2
	Thermal conductivity coefficient, $\text{W/m } ^\circ\text{C}$
K	Dimensionless group describing the the turbulent kinetic energy, k .
L_s	Mixing length, m
Le	Lewis number, $Le_i = \frac{k}{\rho c_p D_{i,m}}$
m	Mass, kg
Nu	Nusselt number, $Nu_L = \frac{hL}{k_f}$
p	Pressure, Pa
Pr	Prandtl Number, $Pr = C_p \mu / k$
Ra	Rayleigh number, $Ra = Gr \times Pr$
Re	Reynolds Number, $Re = \rho U l / \mu$
RH	Relative humidity, %
R_i	Net rate of production of species i
\mathfrak{R}_j	Volumetric rate of creation of species j
S	Source term
	modulus of the mean rate-of-strain tensor
Sc	Schmidt number, $Sc = \nu / D_{im}$
t	Time, s
T	Temperature, K
T'	Temperature fluctuation, K
\bar{u}_i	Mean velocity components, m/s
u'_i	Fluctuating velocity components. m/s