Cairo University

NUMERICAL INVESTIGATION ON EFFECT OF FIRE FIGHTING ON SMOKE MOVEMENT IN TUNNELS.

By

Ramy Mahmoud Ragab Mahmoud

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
2017

NUMERICAL INVESTIGATION ON EFFECT OF FIRE FIGHTING ON SMOKE MOVEMENT IN TUNNELS.

By

Ramy Mahmoud Ragab Mahmoud

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 the Supervision of

Prof. Dr.Mahmoud Ahmed Fouad

Professor of
Mechanical Power Department
Faculty of Engineering, Cairo University

Dr. Taher Mohamed Halawa

Lecturer, Mechanical Power Department

Faculty of Engineering, Cairo University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2017

NUMERICAL INVESTIGATION ON EFFECT OF FIRE FIGHTING ON SMOKE MOVEMENT IN TUNNELS.

By

Ramy Mahmoud Ragab Mahmoud

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. Mahmoud Ahmed Fouad , Thesis Main Advisor

____

Prof. Dr. Samy Mourad, Internal Examiner

____

Prof. Dr. Mohammed Faik Abd Rabbo , External Examiner
Professor of Mechanical Power Department
Faculty of Engineering, Shoubra, Banha University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT
2017

Engineer’s Name: Ramy Mahmoud Ragab Mahmoud

Date of Birth: 10/06/1984
Nationality: Egyption
E-mail: Ramymahmoud37@yahoo.com
Phone: (+2)01119673261

Address: 5 abdmenam ryad St.Madkor,alharam,Giza,Egypt

Registration Date: 01/10/2015
Awarding Date: …./…./2017
Degree: Master of Science
Department: Mechanical Power Engineering

Supervisors:

Prof. Dr. Mahmoud Ahmed Fouad
Dr. Taher Mohamed Halawa

Examiners:

Prof. Dr. Mahmoud Ahmed Fouad (Thesis main advisor)
Prof. Dr. Samy Mourad(Internal examiner)
Porf. Dr Mohammed Faik Abd Rabbo (External examiner)
Professor of Mechanical Power Department
Faculty of Engineering, Shoubra, Banha University

Title of Thesis:

NUMERICAL INVESTIGATION ON EFFECT OF FIRE FIGHTING ON SMOKE MOVEMENT IN TUNNELS.

Key Words:
Smoke Management; Vehicular Tunnels; Ventilation; Visibility; FDS

Summary:
Smoke is the most deadly factor in vehicular tunnels fire since smoke spreads in heading harmonize with passenger’s evacuation way. It reduces visibility and can cause fatalities by suffocation.

This research presents a numerical study of the effect of extracting the smoke by different system of ventilation on smoke spread inside the vehicular tunnel, like (water mist system with transverse ventilation and longitudinal system with jet fans and solid curtain with transverse system and semi transverse system)

Also tenable conditions were checked at human level. FDS 6.5.1 ver. was used to predict the various parameters of temperature, and visibility and Co concentration. Eight cases were conducted; Cases 1, 2, 3 and 7 were done to compare between four different ventilation systems at 30 MW. Case 4, 5, 6 and 8 were done to compare between three different ventilation systems at 100 MW.

Acknowledgment

With the name of **GOD**, I started this research hoping that it accelerates the wheel of progress in this field.

I would like to express my sincere appreciation and infinite thanks to **Professor Dr. Mahmoud Ahmed Fouad**, professor of mechanical power- faculty of engineering– Cairo University, who gave me a great scientific support and guidance to make a progress in my research. Besides, having severe admiration of his gigantic experience and unlimited co-operation and efforts of helping me to introduce this research in the best way.

I would also like to acknowledge the help rendered to me by, **Dr. Taher Mohamed halawa** as advisor, he provided me valuable suggestions and guidance during my study.

In addition, I cannot express; in words; the support of my parents especially my mother, my family. Their insight and wisdom have been invaluable and it's research for my kids (Raseel&Yaseen).

To all my team and my friends: thank you very much for what you have done for me. I thank you all for the companionship that made this journey much easier. In fact, I do not need to list your names because I am sure that you know who you are.

Table of content

ACKNOWLEDGMENT	i
TABLE OF CONTENTS	ii
LIST OF TABLES	Vi
LIST OF FIGURES	Vii
NOMENCLATURE	Xiv
Greek Letters	Xvi
Superscripts and Subscripts	Xvii
Abbreviations	Xviii
ABSTRACT	Xix
CHAPTER 1: INTRODUCTION	1
1.1. General	1
1.2. Hazard of smoke	3
1.2.1 Toxicity	3
1.2.2. High temperature	3
1.2.3. Reduce visibility	4
1.2.4. Back-layering	4
1.3. Objective of smoke management	5
1.4. Plug-Holing	5
1.5. Hazard Of Carbon Monoxide (CO)	6
1.6. Hazard Of Carbon Dioxide (CO2)	7
1.7. High Temperature	8
1.8. Fire Heat Release Rate	8
1.9. Critical Velocity For Smoke Control	9
1.10. Piston Effect At Tunnel	10

1.11. Smoke Stratification 10

1.12. Objective Of Tunnel Ventilation 11

1.13. Tunnel Ventilation 12

1.14. TYPES OF VENTILATION SYSTEM 13

1.14.1 Longitudinal Ventilation 13

1.14.2. Transverse Ventilation 14

1.14.3 Semi-transverse Ventilation 14

1.15. Jet Fans Ventilation 15

1.16 Water Mist Systems 16

1.17 Solid Curtain 17

CHAPTER 2: LITERATURE REVIEW 19

2.1. INTRODUCTION 19

2.2. PREVIOUS WORK 19

2.3. RELATION BETWEEN PREVIOUS WORK AND PRESENT WORK 35

CHAPTER 3: GOVERNING EQUATIONS 36

3.1. DESCRIPTION OF FDS 36

3.1.1. Hydrodynamic Model 36

3.1.2. Combustion Model 36

3.1.3. Radiation Transport 37

3.2. GOVERNING EQUATIONS 37

3.2.1 Mass and Species Transport 37

3.2.2. Momentum Transport 38

3.2.3. Energy Transport 38

3.3. EQUATION OF STATE 39

3.4. LARGE EDDY SIMULATION (LES) 40

3.5. COMBUSTION (MIXTURE FRACTION MODEL) 41

3.6. RADIATION (RADIATION TRANSPORT EQUATION) 42

3.7. THE HEAT CONDUCTION EQUATION FOR A SOLID 44

3.8. RADIATION HEAT TRANSFER TO SOLIDS 44

3.9. CONVECTIVE HEAT TRANSFER TO SOLIDS 45

CHAPTER 4: VALIDATION AND GRID SENSITIVITY ANALYSIS 46

4.1. VALIDATION OF FDS 46

4.1.1. Tunnel Description 46

4.1.2. fire source 46

4.1.3 Ceiling Temperature Measurements 47

4.1.4. FDS Simulations 48

4.1.4. FDS Simulation Results 48

4.2. COMPUTATIONAL DOMAIN AND GRID SENSITIVITY ANALYSIS 49

4.2.1. Tunnel Description 50

4.2.2. fire scenarios 50

4.2.3. Simulation Results 52

4.2.4. Simulation cases of the present study 53

CHAPTER 5 : RESULTS AND DISCUSSIONS 54

5.1. RESULTS OF CASE 1 54

5.2. RESULTS OF CASE 2 59

5.3. RESULTS OF CASE 3 65

5.4. RESULTS OF CASE 4 72

5.5. RESULTS OF CASE 5 76

5.6. RESULTS OF CASE 6 80

5.7. RESULTS OF CASE 7 87

5.8. RESULTS OF CASE 8 **94**

CHAPTER6: CONCLUSIONS AND SUGGESTED FUTURE WORK **102**

6.1. CONCUUSIONS **102**

6.2. SUGGESTED FUTURE WORK **102**

REFERENCES **104**

APPENDIX: APPENDIX **106**

List of Tables

Table 1,1 : Some of road tunnel fires during the last 30 years 2

Table 1,2 : Tenability criteria given by NFPA 502 …………... 4

Table 1,3 : Exposure time and effect of CO ………………….. 7

Table 1,4 : Occupational Exposure Limits for Carbon Dioxide 8

Table 1,5 : Fire Data for Typical Vehicles …………………… 9

Table 1,6 : Tunnel Air Quality Guideline (PIARC) ………….. 15

Table 4,1 : The conditions of the full-scale experiments ……... 48

Table 4,2 : Fire scenarios in numerical simulation …………… 50

Table 4,3 : Cases carried out for sensitivity analyses ………… 51

Table 4,4 : Simulation cases of present study ………………… 53

List of Figures

Figure 1.1 :	Katschberg Road Tunnel, Kärnten, Austria ……………..…………	1
Figure 1.2 :	Back-Layering of smoke …………………………....…...............	4
Figure 1.3 :	Smoke management concept …….….…….….……..…………...	5
Figure 1.4 :	Illustration of Plug holing phenomenon …….….…….………….	6
Figure 1.5 :	Smoke progress in case of a fire in a tunnel (natural ventilation)….	9
Figure 1.6 :	Vvent < Vc (insufficient mechanical ventilation ...………...............	9
Figure 1.7 :	Vvent = Vc (sufficient mechanical ventilation) ....………................	10
Figure 1.8 :	Vvent > Vc (sufficient mechanical ventilation) ....……...…………	10
Figure 1.9 :	Emission standards for new heavy-duty diesel engines, relative to Euro I …………………………….……..............................	13
Figure 1.10:	Longitudinal & Transverse & Semi transverse ventilation ………..	14
Figure 1.11:	Jet fans used for ventilating the Mrazovka tunnel, Prague ……………………………………….….….…….	15
Figure 1.12:	Jet fan theory of operation ……………………………………….	16
Figure 1.13:	Test in tunnel by water mist system in Germany …………………...	17
Figure 1.14:	Solid curtain in ceiling of the tunnel………………………………...	18
Figure 2.1 :	Layout of Vehicular Tunnel ………………………………...............	20
Figure 2.2 :	Tunnel cross-section ………………………………………..............	21
Figure 2.3 :	Illustration of experimental arrangement for plan of the model tunnel ……………………………………………..........................	22
Figure 2.4 :	The scale tunnel model, inclination angle adjustment ……..............	23
Figure 2.5 :	A partial view of the full-scale tunnel fire experimental setup …………………………………………………....................	25

Figure 2.6 :	Structural diagram of the multi-branch tunnel …………….……..	26
Figure 2.7 :	The convective HRR and the rate of smoke particle generation as well as pictures of the full-scale model tunnel fire experiment …………………………………….....…………………	27
Figure 2.8 :	Sketch of two types of compartmentalization in tunnel …….……	28
Figure 2.9 :	Influence of ventilation velocity on the fire growth rate …………	29
Figure 2.10:	Nanjing Xi'anmen Tunnel with roof opening ……………………	31
Figure 2.11:	Critical velocity with the tunnel slope ……………………………	32
Figure 2.12:	Spray shapes of nozzles with 5 L/ min. (a) 60°, (b) 90° (c) 120°…	33
Figure 2.13:	Setup of Water Distribution test ………………………...………	34
Figure 4.1 :	Physical model for simulations Geometry of the simulation tunnel configuration (not in scale) ………………………….……………..	46
Figure 4.2 :	A partial view of the full-scale tunnel fire experimental setup ……………………………………………………...…………..	47
Figure 4.3 :	Typical HRR as a function of time from the ethanol pool fires for four pans based on the measured mass loss rate ….........................	47
Figure 4.4 :	Comparison of temperature variation between simulation and experimental results ………………..…………………..................	49
Figure 4.5 :	Comparison of HHR variation between simulation and experimental results …………………………………………..........	49
Figure 4.6 :	Schematic diagram of arrangement of fire source, vents and water mist nozzles ……………………………..….…….….….…….	50
Figure 4.7 :	The temperature at 0.05 m under the ceiling ………….......……...	51
Figure 4.8 :	Comparison for Numerical temperature distributions at 4.95 m above the tunnel floor …………………………………….……….	52
Figure 4.9 :	Comparison for Numerical visibility distributions at 2.0 m above the floor level ……………………………………….………………	52

Figure 4.10: Comparison for Numerical CO concentration distributions at 2.0 m above the floor level ……………………………….…………… 53

Figure 5.1 : Schematic diagram of the arrangement of fire source, vents and water mist nozzles in case 1 …………………………………… 54

Figure 5.2 : Smoke spread process in case 1 at 60 s, 180 s, 240 s, and 300 s ……………………………………………………...………… 55

Figure 5.3 : Temperature contours distributions along the tunnel in case 1 at side View (at 60 s, 180 s, 240 s, and 300 s) ……………………… 56

Figure 5.4 : Numerical temperature distribution at 4.95 m above the tunnel floor in case 1 …………………………………..……………… 56

Figure 5.5 : Numerical visibility distributions in case 1 at human level at 2 m (at 60 s, 120 s, 180 s, 240 s, and 300 s)………….………… 57

Figure 5.6 : Visibility distributions along the tunnel in case 1 at side view (at 60 s, 120 s, 180 s, 240 s, and 300 s)…………………… 58

Figure 5.7 : Numerical visibility distributions at 2.0 m above the floor level in case 1……………………………………..………… 58

Figure 5.8 : Numerical CO concentration distributions at 2.0 m above the floor level in case 1……………………………………… 59

Figure 5.9 : Schematic diagram of the arrangement of fire source, jet fans system ventilation in case 2…………………………………… 59

Figure 5.10: Smoke spread process in Case 2 at 60 s, 120 s, 180 s, 240 s, and 300 s …..…… 60

Figure 5.11: Numerical temperature distributions along the tunnel in case 2 at human level at 2 m (at 60 s, 120 s, 180 s, 240 s, and 300 s)…….. ….….… 60

Figure 5.12: Temperature contours distributions along the tunnel in case 2 at side view (at 60 s, 120 s, 180 s, 240 s, and 300 s)……………… 61

Figure 5.13: Comparison between temperature distributions at 0.05 m under the ceiling in Case 1 & Case 2 ……........................………………. 61

Figure 5.14: Numerical visibility distributions in case 2 at human level at 2 m (at 60 s, 120 s, 180 s, 240 s, and 300 s)..............................…. 62

Figure 5.15: Visibility contours distributions along the tunnel in case 2 at side view (at 60 s, 120 s, 180 s, 240 s, and 300 s)…………… 63

Figure 5.16:	Comparison between visibility distributions at 2.0 m above the floor level in Case 1 & Case 2 …………………………	63
Figure 5.17:	Numerical CO concentration distributions at 2.0 m above the floor level in case 2……………………………………	64
Figure 5.18:	Comparison between CO concentration distributions at 2.0 m above the floor level in Case 1 & Case 2 ………………………………	65
Figure 5.19:	Schematic diagram of the arrangement of fire source, vents and Solid Curtains in case 3……..…..…..…..…..…..…..…..…..	65
Figure 5.20:	Smoke spread process in Case 3 at (60 s, 120 s, 180 s, 240 s, and 300 s)……………………. ……………	66
Figure 5.21:	Comparison between Smoke spread distributions at (300 s) in Case 1 & Case 2& Case 3 @30MW …………	67
Figure 5.22:	Numerical temperature distributions along the tunnel in case 3 at human level at 2 m (at 60 s, 120 s, 180 s, 240 s, and 300 s) ………………………………………………	68
Figure 5.23:	Temperature contours distributions along the tunnel in case 3 at side view (at 60 s, 120 s, 180 s, 240 s, and 300 s)…………………	68
Figure 5.24:	Comparison between temperature distributions at human level at 2 m (at 300 s) in Case 1 & Case 2& Case 3 @30MW ……………… ………………………………	69
Figure 5.25:	Numerical visibility distributions along the tunnel in case 3 at human level (at 60 s, 120 s, 180 s, 240 s, and 300 s)…………..	70
Figure 5.26:	Visibility contours distributions along the tunnel in case 3 at side view (at 60 s, 120 s, 180 s, 240 s, and 300 s)…………………….	70
Figure 5.27:	Comparison between visibility distributions at human level at 2 m (at 300 s) in Case 1 & Case 2& Case 3 @30 MW ………………………………………	71
Figure 5.28:	Numerical CO concentration distributions at 2.0 m above the floor level in case 3……………………	72
Figure 5.29:	Schematic diagram of the arrangement of fire source, vents and water mist nozzles in case 4……………………………….	72
Figure 5.30:	Smoke spread process in Case 4 at (60 s, 120 s, 180 s, 240 s, and 300 s)…………………………………………………………..	73
Figure 5.31:	Numerical temperature distributions along the tunnel in case 4 at human level at 2 m (at 60 s, 120 s, 180 s, 240 s, and 300 s)………………………	74

Figure 5.32:	Temperature contours distributions along the tunnel in case 4 at side view (at 60 s, 120 s, 180 s, 240 s, and 300 s)…..	74
Figure 5.33:	Visibility slices at the center section of the tunnel at human level at 2 m above the tunnel floor (at 60 s, 120 s, 180 s, 240 s, and 300 s)	75
Figure 5.34:	Numerical CO concentration distributions at 2.0 m above the floor level in case 4. ……………………………………	76
Figure 5.35:	Schematic diagram of the arrangement of fire source, jet fans system ventilation in case 5……………………………………	76
Figure 5.36:	Smoke spread process in Case 5 at 60 s, 120 s, 180 s, 240 s, and 300 s ………………	77
Figure 5.37:	Numerical temperature distributions along the tunnel in case 5 at human level (at 60 s, 120 s, 180 s, 240 s, and 300 s)………………	78
Figure 5.38:	Temperature contours distributions along the tunnel in case 5 at side view (at 60 s, 120 s, 180 s, 240 s, and 300 s)………………	78
Figure 5.39:	Numerical visibility distributions along the tunnel in case 5 at human level (at 60 s, 120 s, 180 s, 240 s, and 300 s)…………..	79
Figure 5.40:	Visibility contours distributions along the tunnel in case 5 at side view (at 60 s, 120 s, 180 s, 240 s, and 300 s)	79
Figure 5.41:	Numerical CO concentration distributions at 2.0 m above the floor level in case 5…………………………………	80
Figure 5.42:	Schematic diagram of the arrangement of fire source, vents and Solid Curtain system in case 6……………………………………	80
Figure 5.43:	Smoke spread process in Case 6 at (60 s, 120 s, 180 s, 240 s, and 300 s)…	81
Figure 5.44:	Comparison between Smoke spread distributions (at 300 s) in Case 4 & Case 5 & Case 6 @100MW ………………	82
Figure 5.45:	Numerical temperature distributions along the tunnel in case 6 at human level@2 m (at 60 s, 120 s, 180 s, 240 s, and 300 s)…………	83
Figure 5.46:	Temperature contours distributions along the tunnel in case 6 at side view (at 60 s, 120 s, 180 s, 240 s, and 300 s)………………	83
Figure 5.47:	Comparison between temperature distributions at human level at 2 m (at 300 s) in Case 4 & Case 5 & Case 6 @100 MW …………	84