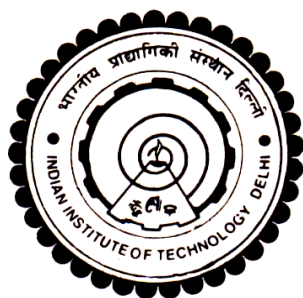


**DESIGN AND OPTIMIZATION OF AIR VENTILATION
SYSTEM FOR IMPROVED HEAT TRANSFER
CHARACTERISTICS IN HELMETS**

SHISHODIA BHAGWATSINGH DASHRATHSINGH



**DEPARTMENT OF APPLIED MECHANICS
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

FEBRUARY 2017

**DESIGN AND OPTIMIZATION OF AIR
VENTILATION SYSTEM FOR IMPROVED HEAT
TRANSFER CHARACTERISTICS
IN HELMETS**

by

SHISHODIA BHAGWATSINGH DASHRATHSINGH

DEPARTMENT OF APPLIED MECHANICS

**Submitted
in fulfilment of the requirements of the degree of Doctor of Philosophy
to the**



INDIAN INSTITUTE OF TECHNOLOGY DELHI

FEBRUARY 2017

CERTIFICATE

*This is to certify that the thesis titled “**Design and Optimization of Air Ventilation System for Improved Heat Transfer Characteristics in Helmets**” being submitted by **Mr. Shishodia Bhagwatsingh Dashrathsingh** to the **Indian Institute of Technology Delhi**, for the award of the degree of **Doctor of Philosophy** in Department of Applied Mechanics is a bonafide research work carried out by him under our supervision and guidance. The research work presented in this thesis has not been submitted in parts or in full to any other University or Institute for the award of any degree or diploma.*

Sanjeev Sanghi, Ph.D.
Professor
Dept. of Applied Mechanics,
Indian Institute of Technology Delhi
New Delhi-110016, India

Puneet Mahajan, Ph.D.
Professor
Dept. of Applied Mechanics,
Indian Institute of Technology Delhi
New Delhi-110016, India

Date:

Place: New Delhi

ACKNOWLEDGEMENTS

I wish to offer my gratitude to everyone for helping me in this long journey of obtaining Ph.D. This thesis is the result of persistent hard work of over six years, whereby I have been taught, supported and motivated by many people, which enabled me to accomplish this mammoth task. I would like to offer my sincere thanks to everyone who directly or indirectly contributed in completion of this thesis.

The research topic grew out of series of discussion with my two supervisors Professor Sanjeev Sanghi and Professor Puneet Mahajan. Through their deep knowledge and rich experience they made me understand this topic to a greater depth. They also made be aware of the social cause behind this study.

Professor Sanjeev Sanghi is a person with vast knowledge, incomparable insights and humanity. I feel very lucky in having him as my supervisor. His encouraging words and unwavering support always motivated me during the turbulent phases of my research. With his rich experience and enormous patience he helped me in tying up all the loose ends of my research. With immense pleasure, I wish to express my heartfelt gratitude and indebttness to Professor Sanjeev Sanghi.

Words fail me to express my gratitude to Prof. Puneet Mahajan for his support and encouragement. His in-depth knowledgeable and research abilities can make anyone envy of him. He is the epitome in his field of research and teaching. His abilities to minutely observe and understand the problem is beyond comparison. He is a person of extremely high values, ethics and conviction. Thank you sir, I am deeply beholden to you.

I am also extremely obliged to my student research committee chairman Prof. Anupam Dewan, for encouraging me in my research work. I am also very much thankful to Dr. Balaji Shrinivasan making me understand the concepts of computational fluid dynamics. I warmly thank Prof. Ratan Mohan, for his valuable advice and constructive suggestions on this work. Thanks to all the faculty members of the Departmental Research Committee and Applied Mechanics Department for providing me the valuable inputs in my research. I also wish to thank Prof. Peter Childs and Prof. Anthony Bull for providing me opportunity to work on my research topic at Imperial College London.

I would like to extend my sincere thanks to Dr. Anubhav Rawat for his untiring help during my research duration, best wishes to you for your postdoctoral research. I wish to thank Dr. Rajesh Kumar, Dr. Vivek Patel, Dr. Rabhijeet, Mr. Abhimanyu, Mr. Anuj Shukla, Mr. Arun Baby, Mr. Sandeep Sikri, Mr. Hamid, Mr. Pratanshu, Mr. Haroon, Mr. Lakhivandar Singh and Mr. Shrish shukla for their unconditional support.

I owe my utmost gratitude to my parents, wife, daughter and family members for inspiring me in completion of my research. During the difficult times in research, the encouragement and faith of my wife in me is unforgettable, it is her sacrifices that made it possible. Thank you Neelu. Love and affection of daughter can bring smile and peace to any father. Thanks Yuvika for your unconditional love and support. Above all, thanks to '**All Mighty God**' for giving me strength and ability to work hard. It is he, who showed me the right path in the moment of darkness.

(Shishodia Bhagwatsingh Dashrathsingh)

ABSTRACT

In tropical countries there is reluctance to wear motorcycle helmets in hot summer days due to the discomfort caused by sweating and high temperature. A computational study is carried out to see if providing vents in the helmet reduce this discomfort. Results of computational fluid dynamics (CFD) simulations are then used to predict the thermal comfort of the riders. Front impact absorption tests are then performed to ascertain whether vents affect the safety of the helmets. Subjective human trials of newly designed helmets are also done to correlate the ventilation in helmets and the willingness of the riders to wear helmets at higher temperatures.

In the absence of any universal turbulence model for predicting mean flow parameters, the best turbulence model for predicting air flow in the air gap of helmet is first found. This is accomplished by comparing experimental result of the air flow in the air gap of a 3-dimensional hemispherical head-helmet arrangement and the numerical results of the air flow in the same arrangement using different turbulence models. It is found that Spalart - Allmaras model predicts the mean flow parameters better than $k - \varepsilon$ model for the above arrangement. Air flow simulations are then performed on Computer Aided Design (CAD) model of 3-dimensional full-face motorcycle helmets to investigate the effect of vents on the air flow in the air gap of a ventilated helmet. The results of air flow simulations are used to optimize the number of vents and their locations on the helmet. Number of supports to raise the helmet above rider's head is also determined using the results of air flow simulations.

Human thermoregulation simulations are performed using a CFD code coupled with a numerical model of human thermoregulation system, to investigate

the thermal flow in the air gap of full face motorcycle helmets. The scope of the investigation includes the effects of the air gap size, the ventilation or otherwise of the helmet, the effects of ambient air temperature and the relative humidity on the thermal comfort of the rider. The numerical results are presented in terms of average temperature, Apparent Temperature (AT) and Wet Bulb Global Temperature (WBGT). Results suggest that 36°C can be considered as threshold temperature, beyond which if the air inlet temperature is increased, the ventilated helmet becomes less conducive to the riders. Results also indicate that with the increase in relative humidity of air, the thermal comfort of a rider decreases.

Front Impact absorption test on three ventilated helmets and one non ventilated helmet were then performed. Maximum head acceleration in the direction of impact is recorded to be 212.3g, 205.1g and 198.1g for three ventilated helmets and 219.2g for non ventilated helmet. Head Injury Criterion (HIC_{36}) is also calculated and it is found to be 1391.2, 1078.9 and 1034.4 for ventilated helmets and 1343.4 for non ventilated helmet. Results indicate that ventilated helmet satisfies the Bureau of Indian Standard (BIS) 4151 safety criterion and is safe to wear.

Subjective human trials are also performed on forty riders for forty eight sets of trials under different environmental conditions. Results indicate that 94% riders found ventilated helmet comfortable below 36°C. In temperature range of 36°C to 38°C, 81% riders found ventilated helmets comfortable and only 19 % riders found ventilated helmet comfortable beyond 38°C. The results strongly correlate the ventilation in helmets and the willingness of riders to wear helmets at higher temperatures. Finally, a fluid dynamic guideline for helmet manufacturers is also suggested for improving ventilation in helmets.

सार (ABSTRACT IN HINDI)

उष्णकटिबंधीय देशों में गर्मी के मौसम में उच्च तापमान तथा अत्यधिक पसीने के कारण मोटरसाइकिल सवार हेलमेट पहनने में परेशानी तथा अनिच्छा अनुभव करते हैं। हेलमेट में सुराख उपलब्ध कराने से मोटरसाइकिल सवार को गर्मी के मौसम में इस परेशानी से निजात मिल सकती है की नहीं? यह जानने के लिए एक कम्प्यूटेशनल अध्ययन किया गया है। कम्प्यूटेशनल फ्लूइड डायनामिक्स (सीएफडी) सिमुलेशन के परिणाम से यह भविष्यवाणी करने में मदद मिलेगी की मोटरसाइकिल सवार को सुराखदार हेलमेट पहनने से कितना उष्ण (थर्मल) आराम मिलेगा। इसके पश्चात हेलमेट के सामने की तरफ प्रभाव अवशोषण परीक्षण यह पता लगाने के लिए किया गया है की, क्या सुराख करने से हेलमेट की सुरक्षा प्रदान करने की क्षमता प्रभावित तो नहीं हुई है? नए डिजाइन वाले हेलमेट के व्यक्तिपरक मानव परीक्षण भी किये गए हैं। यह परीक्षण उच्च तापमान पर हेलमेट में वेंटिलेशन और मोटरसाइकिल सवार की हेलमेट पहनने की इच्छा के बीच सम्बन्ध स्थापित करने के लिए किए गए हैं।

सर्व प्रथम, प्रवाह मानकों की भविष्यवाणी के लिए किसी भी सार्वभौमिक अशांति (टर्बुलेन्स) मॉडल के अभाव के कारण, हेलमेट के हवा प्रवाह स्थान (एयर गैप) में हवा के प्रवाह की भविष्यवाणी के लिए सबसे अच्छा अशांति

(टर्बुलेन्स) मॉडल का पता लगाया गया है । यह एक 3-आयामी अर्धगोल सिर से हेलमेट व्यवस्था की एयर गैप में हवा का प्रवाह और संख्यात्मक अलग अशांति मॉडल का उपयोग कर एक ही व्यवस्था में हवा का प्रवाह के परिणामों की प्रयोगात्मक परिणाम की तुलना द्वारा पूरा किया गया है। ऊपर उल्लिखित प्रयोगिक व्यवस्था के लिए यह पाया गया है कि स्पलार्ट - अलमर्स (Spalart - Allmaras) मॉडल, के - एप्सिलोन ($k - \epsilon$) मॉडल से प्रवाह मानकों की बेहतर भविष्यवाणी करता है । ततः पश्चात मोटरसाइकिल हेलमेट के हवा प्रवाह के लिए स्थान (एयर गैप) में हवा के प्रवाह पर सुराखों के प्रभाव की जांच करने के लिए कम्प्यूटर एडेड डिजाइन (सीएडी) की मदद से 3-आयामी, पूर्ण चेहरा, सुराखदार हेलमेट बनाये गए, जिन पर वायु प्रवाह सिमुलेशन किये गए । हवा के प्रवाह का सिमुलेशन के परिणामों का इस्तेमाल हेलमेट पर सुराखों की संख्या तथा उनका स्थान अनुकूलन करने के लिए किया गया । हेलमेट को मोटरसाइकिल सवार के सर से ऊपर उठने हेतु, समर्थनो (सपोर्ट्स) की समुचित संख्या निर्धारित करने के लिए भी हवा के प्रवाह के सिमुलेशन के परिणामों का उपयोग किया गया है ।

मानव के तापमान का सिमुलेशन, एक मानव तापमान प्रणाली के संख्यात्मक मॉडल को सीएफडी कोड के साथ मिलाकर पूरा चेहरा मोटरसाइकिल हेलमेट के हवा

प्रवाह स्थान (एयर गैप) में उष्ण (थर्मल) प्रवाह की जांच करने के लिए किया गया है। जांच के दायरे में हेलमेट में हवा प्रवाह स्थान के माप (एयर गैप साइज), हवादार (वेंटिलेटेड) हेलमेट या हेलमेट के बिना, परिवेशी वायु तापमान और सापेक्ष आर्द्रता का मोटरसाइकिल सवार के थर्मल आराम पर पड़ने वाले प्रभाव का अध्ययन भी शामिल है। संख्यात्मक परिणामों को औसत तापमान, स्पष्ट तापमान और गीला बल्ब वैश्विक तापमान (WBGT) के अनुसार प्रस्तुत किया गया है। संख्यात्मक परिणाम यह सुझाव देते हैं कि 36°C एक तापमान सीमा है, जिससे अधिक तापमान से, यदि हवा हेलमेट में प्रवेश करती है तो, मोटरसाइकिल सवारों को हवादार हेलमेट कम अनुकूल लगेगा। संख्यात्मक परिणामों से यह संकेत भी मिलता है कि हवा के सापेक्ष आर्द्रता में वृद्धि के साथ एक मोटरसाइकिल सवार का थर्मल आराम घट जाता है।

तीन हवादार हेलमेट और एक गैर हवादार हेलमेट पर सामने प्रभाव अवशोषण परीक्षण किया गया। प्रभाव की दिशा में अधिकतम सिर त्वरण (एक्सीलरेशन) 212.3g, 205.1g और 198.1g तीन हवादार हेलमेट के लिए और 219.2g गैर हवादार हेलमेट के लिए दर्ज की गई है। सिर पर चोट कसौटी (HIC36) की गणना भी की गई है और यह हवादार हेलमेट के लिए 1391.2, 1078.9 और 1034.4 तथा गैर हवादार हेलमेट के लिए 1,343.4 पाई गई है। परिणामों से यह संकेत मिलता है कि हवादार हेलमेट भारतीय मानक ब्यूरो

(बीआईएस) 4151 की सुरक्षा कसौटी को संतुष्ट करते हैं और मोटरसाइकिल सवार के पहनने के लिए सुरक्षित हैं।

विभिन्न पर्यावरणीय परिस्थितियों में 40 सवारों पर 48 सेट व्यक्तिपरक मानव परीक्षण भी किये गए हैं। व्यक्तिपरक मानव परीक्षण परिणामों से यह संकेत मिलता है कि 94% सवारों ने हवादार हेलमेट को 36°C के नीचे आरामदायक पाया है | 81% सवारों ने 36°C से 38°C तापमान रेंज में हवादार हेलमेट को आरामदायक पाया और केवल 19% सवारों ने हवादार हेलमेट को 38°C से अधिक तापमान पर आरामदायक पाया। ऊपर उल्लिखित परिणाम हेलमेट में वेंटिलेशन और सवार की उच्च तापमान पर हेलमेट पहनने की इच्छा के बीच सम्बन्ध दर्शाते हैं | अंत में हेलमेट में वेंटिलेशन के सुधार के लिए, हेलमेट निर्माताओं को द्रव गतिशील दिशानिर्देश के तौर पर सुझाव भी दिए गए हैं।

TABLE OF CONTENT

CERTIFICATE	i
ACKNOWLEDGEMENTS	ii
ABSTRACT	iv
संक्षेप (ABSTRACT IN HINDI)	vi
TABLE OF CONTENTS	x
LIST OF FIGURES	xiv
LIST OF TABLES	xx
NOMENCLATURE	xxi
ACRONYMS	xxv
CHAPTER 1 INTRODUCTION	1
1.1 Motivation	1
1.2 Introduction	2
1.3 Organization of the thesis	4
CHAPTER 2 LITERATURE SURVEY	7
2.1 Helmet and its technical features	7
2.2 Computational Fluid Dynamics (CFD) analysis of Air Flow in a Helmet	9
2.3 Sweat Evaporation and Thermodynamic of Flow in Helmet	12
2.4 Coupling CFD and Human Body Thermoregulation Model	16
2.5 Optimization of Air Ventilation System of Helmet	20
2.6 Impact analysis of helmet	24
2.7 Psychological and Cognitive effects of wearing helmet	28
2.8 Conclusion form literature survey and gaps in studies	30
2.9 Objective of the Present Study	33
CHAPTER 3 VENTILATION IN FULL FACE MOTORCYCLE HELMETS	34
3.1 Computational fluid dynamics (CFD)	35
3.1.1 Mathematical formulation	36
3.1.2 Turbulence modeling	44
3.1.3 Finite Volume Method	52

3.2	Turbulence model for predicting air flow in helmets	53
3.2.1	Numerical simulations of air flow in pipe	55
3.2.2	Numerical simulations of air flow in Lid Driven cavity flow	57
3.2.3	CFD Simulations of Air Flow in 3- D Hemispherical Head-Helmet Model	59
3.3	Numerical simulations of air flow in a full face motorcycle helmet for estimating the effectiveness of vent in a helmet	62
3.4	Numerical simulations of air flow in full face helmet with modified Neck Curtain	67
3.5	Numerical simulations of air flow in full face helmet for optimizing the number of vents in a helmet	70
3.6	Arrangements of supports in a ventilated helmet	71
3.7	Result and Discussion	73
CHAPTER 4	NUMERICAL SIMULATIONS OF HUMAN THERMOREGULATION MODEL	76
4.1	Human thermal comfort	77
4.1.1	Measurement of thermal comfort: Environmental Indices	79
4.1.2	Thermal comfort standards	81
4.2	Human Thermoregulation	82
4.2.1	Human thermoregulation in hot	83
4.2.2	Human Thermoregulation in cold	84
4.3	Mathematical model of human thermoregulation	85
4.4	JOS Human thermoregulation model	89
4.5	Coupling CFD and human thermoregulation	91
4.6	Over view of CFD simulations of air flow and JOS Human Thermoregulation	92
4.7	Results of CFD Simulations of Air Flow and JOS Human Thermoregulation	94
4.7.1	Qualitative comparisons of numerical results of air flow and heat transfer in the helmet air gap	95
4.7.2	Effect of increase in ambient air temperature on the thermal comfort of a rider	99

	4.7.3 Effect of increase in relative humidity of air on the thermal comfort of a rider	108
	4.8 Discussion	112
CHAPTER 5	DESIGN MODIFICATION IN VENTILATED HELMET	114
5.1	Ventilated helmet with venturi effect	115
5.1.1	Study of airflow in helmet with venturi effect	117
5.1.2	Effect of increase in ambient air temperature on the thermal comfort of a rider	119
5.2	Ventilated helmet with venturi effect and a back-vent	130
5.2.1	Study of airflow in helmet with venturi effect and a backvent	131
5.2.2	Effect of increase in ambient air temperature on the thermal comfort of a rider	133
5.3	Discussion	139
CHAPTER 6	IMPACT ANALYSIS OF HELMETS	140
6.1	Structure of human head	142
6.2	Mechanisms of head injuries	142
6.3	Types of head injuries	144
6.4	Standards for motorcycle helmet and impact tests	145
6.5	Prototype of modified ventilated helmet	147
6.6	Front Impact testing on helmet	148
6.6.1	Dynatup Impact testing machine	148
6.6.2	Accelerometer	150
6.6.3	Experimental setup for front impact testing of helmet	151
6.6.4	Calibration of the load cell in the Dynatup Impact Testing Machine	152
6.7	Results	153
6.7.1	Qualitative comparison of impact test	154
6.7.2	Impact force as a function of time during impact test	155
6.7.3	Deceleration as a function of time during impact test	156

6.7.4	Head Injury Criterion	157
6.8	Discussion	159
CHAPTER 7	SUBJECTIVE EVALUATION OF HELMET PROTOTYPE	160
7.1	Effects of wearing helmet on psychological and cognitive abilities of rider	162
7.2	Subjective human trial	164
7.2.1	Participants	165
7.2.2	Weather conditions during trials	166
7.2.3	Journey details	166
7.2.4	Pre-Trial Questionnaire	166
7.2.5	Post Trail Questionnaire	167
7.3	Protocols Used for Performing Subjective Human Trails	168
7.4	Results of Trails	169
7.4.1	Results of riders survey	169
7.4.2	Results of driving trials of Powered Two Wheelers	172
7.4.3	Discussion	175
7.5	Design of automatic vent closing mechanism	175
CHAPTER 8	CONCLUSION	177
8.1	Conclusions	177
8.2	Fluid dynamic guideline for helmet manufacturers	181
8.3	Scope for future work	182
	REFERENCES	184
	APPENDIX	194
	LIST OF PUBLICATIONS	207
	BRIEF BIO DATA OF AUTHOR	209

LIST OF FIGURES

Fig. No.	Title of Figure	Page No.
2.1	Technical features of motorcycle helmet	8
2.2	Schematic view of experimental model [9]	10
2.3	CFD simulation results of different slot orientation in helmet [9]	22
2.4	Experimental Setup for drop test of helmet [2]	26
3.1	Dimensions of pipe and Boundary condition	55
3.2	Grid Independence in Pipe flow	55
3.3	Velocity profile at different Reynolds number	56
3.4	Turbulent viscosity ratio as a function of radial distance	57
3.5	Lid Driven Cavity geometry and boundary conditions	58
3.6	U- Velocity at vertical line through centre for Different Reynolds number	58
3.7	Experimental Model (courtesy: Yadav [87]) and Meshing in 3-Dimensional hemispherical model of helmet for CFD Simulation	59
3.8	Grid independence for 3-Dimensional Hemispherical-Head Helmet Arrangement	60
3.9	Computational domain for CFD Simulation	60
3.10	Comparison of x-velocities on a vertical line at the centre of the air gap at the top of head in a hemispherical helmet	61
3.11	Full face motorcycle helmet with single air vents in front	62
3.12	(a) Full face motorcycle helmet without vent (b) Full face motorcycle helmet with three air vents in front	63
3.13	Different prism layers for simulating air flow in the air gap of helmet	63
3.14	(a) Pseudo head surface 1 mm away from head (b) Velocity comparison for grid independence of three dimensional helmets	64
3.15	Domain for CFD simulations	65

Fig. No.	Title of Figure	Page No.
3.16	Stream lines of air flow in the air gap of helmet	65
3.17	Qualitative comparison of ventilated and non ventilated helmet	66
3.18	Comparison of air flow at the exit in ventilated and non ventilated helmet	66
3.19	Neck curtain in helmet	67
3.20	Modified Neck Curtain at the back of helmet	68
3.21	Comparison of air flow in ventilated helmet with and without modified neck curtain	68
3.22	(a) Eighty points 1 mm away from head on central plane (b) Comparison of magnitude of velocity on Eighty points 1mm away from head on central plane	69
3.23	Front View of Full face motorcycle helmet with three different arrangements of air vents	70
3.24	Points 1mm away from head and comparison of velocities on central plane along the direction of flow	71
3.25	Design of support for raising helmet above head	72
3.26	Arrangements of supports in the helmet with (a) Five Supports (b) Four Supports	72
3.27	Comparison of magnitude of velocities on central plane along the flow direction	73
4.1	Thermal comfort chart during summer and winter	82
4.2	Human thermoregulation mechanisms	84
4.3 (a)	JOS body Segmentation model [15]	85
4.3 (b)	Conceptual figure of 65 Node thermoregulation system	86
4.4	Cross section of a Segment	89
4.5 (a)	Flow Chart of JOS- CFD calculation	91
4.5 (b)	Boundary conditions used for CFD and JOS Human thermoregulations simulations	92
4.6	CAD geometry of helmet with and without vents.	92

Fig. No.	Title of Figure	Page No.
4.7	Domain for CFD simulations of airflow and Human Thermoregulation	93
4.8	Qualitative comparison of velocity when air entered domain inlet with a velocity of 15 m/s: (a) 2mm raised helmet (b) 6 mm raised helmet (c) ventilated and 6mm raised helmet (d) No helmet	97
4.9	Qualitative comparison of temperature in the air gap of helmet at central plane when air inlet temperature is 30°C: (a) 2mm raised helmet (b) 6mm raised helmet (c) ventilated and 6mm raised helmet (d) No helmet	98
4.10	Eighty points 1 mm away from head on central plane	100
4.11	Comparison of Temperature and AT on central plane along flow direction	101
4.12	Surface 1mm above head	102
4.13	Velocity contours on a surface 1mm away from head, when the air inlet velocity is 15 m/s in x- direction for: (a) 2mm raised helmet (b) 6mm raised helmet (c) ventilated and 6mm raised helmet (d) No helmet	103
4.14	Temperature contours on a surface 1mm away from head when the air inlet temperature is 30°C for: (a) 2mm raised helmet (b) 6mm raised helmet (c) ventilated and 6mm raised helmet (d) No helmet.	105
4.15	Comparison of (a) temperature, (b) AT and (c) WBGT on a surface 1mm away from head. (X-axis represents air inlet temperature in °C)	106
4.16	Effect of Relative humidity on Apparent Temperature (AT) at different air inlet temperatures	109
4.17	Effect of increases in relative humidity of air on (a) temperature, (b) AT and (c) WBGT heat indices on a surface 1mm away from head	111

Fig. No.	Title of Figure	Page No.
5.1	Schematic Diagram of Arrangement of supports and modified neck curtain for creating “Venturi Effect” in helmet	116
5.2	Location of circular plane in the air gap	118
5.3	Average value of velocity at the Cross section in the air gap	118
5.4	Qualitative comparison of velocity distribution on central plane for : (a) Helmet without venturi effect (b) Helmet with venturi effect	120
5.5	Temperature distribution on central plane in : (a) Helmet without venturi effect (b) Helmet with venturi effect	122
5.6	Points 1mm away from head on central plane	123
5.7	Comparison of Temperature and AT on central plane along flow direction on 80 points 1mm away from head	124
5.8	Velocity contours on a surface 1 mm away from head, when the air inlet velocity is 15 m/s in x- direction for: (a) 2 mm raised helmet (b) ventilated and raised helmet (6 mm-6 mm) (c) Venturi Helmet (6 mm-2 mm) (d) No helmet	126
5.9	Temperature contours on a surface 1 mm away from head when the air inlet temperature is 30°C for: (a) 2 mm raised helmet (b) ventilated and raised helmet (6 mm-6 mm) (c) Venturi Helmet (6 mm-2 mm) (d) No helmet.	127
5.10	Comparison of (a) $T_{average}$ (b) AT and (c) WBGT on a surface 1mm away from head. (X-axis represents air inlet temperature in °C)	129
5.11	Design of venturi helmet with single backvent	130
5.12	Stream lines of air flow in venturi helmet with single backvent	131

Fig. No.	Title of Figure	Page No.
5.13	Velocity distribution on central plane in a helmet with single back vent	132
5.14	Eighty points on central plane in the air gap of (a) Venturi helmet with Backvent (b) Venturi Helmet (c) No Helmet condition	134
5.15	Comparison of Temperature and AT on central plane along flow direction	135
5.16	Comparison of (a) Taverage (b) AT and (c) WBGT on a surface 1mm away from head. (X-axis represents air inlet temperature in °C)	138
6.1	Mechanism of head injuries	143
6.2	Components of a full face motorcycle helmet	145
6.3	Prototype of a modified ventilated helmet	148
6.4	Schematic diagram of Instron Dynatup Impact Testing machine	149
6.5	Experimental setup for front impact absorption Test	151
6.6	Standard impact sites on the helmet B-front, C-crown, S- side, R-rear impact regions, BIS4151	152
6.7	Headform strapped with (a) Ventilated Helmet (b) Non - Ventilated helmet for calibration and front Impact test	153
6.8	Deformation in ventilated helmet (Vent 1) after front impact test	154
6.9	Deformation in non ventilated helmet (No vent) after front impact test	154
6.10	Impact force on the helmet shell front impact test at point B	156
6.11	Deceleration of head form during front impact absorption test at point B with a velocity of 7.5 m/s in vertically downward direction	157
6.12	Comparison of HIC for different helmets	159
7.1	Relationship between full face motorcycle helmet and traffic safety (Courtesy: Bogerd et al. [57]).	163

Fig. No.	Title of Figure	Page No.
7.2	Rider's reasons for feeling uncomfortable while riding wearing a non- ventilated conventional helmet	170
7.3	Rider's perceptions of ventilation provided in their existing helmet	171
7.4	Rider's area of concern for helmet design	172
7.5	Results of Subjective Human trials of modified helmet	173
7.6	Rider's reasons for feeling comfortable in ventilated helmet	173
7.7	Rider's view of improvement in their cognitive abilities wearing "Venturi" helmet as compared with ventilated helmet	174
7.8	Automatic Vent Closing Mechanism	176
8.1	Isometric and top view of design modifications in conventional full face helmet	182

LIST OF TABLES

Table. No.	Title of Figure	Page No.
3.1	Empirical constants and their values used in Standard $k - \varepsilon$ model	49
3.2	Empirical constants and their values used in RNG $k - \varepsilon$ model	51
3.3	X-Velocity and Average root mean square deviations of X-velocity for different turbulence models.	61
6.1	Mass of various moving parts for calibration of load cell	155

NOMENCLATURE

Symbol	Meaning
a	Ratio of counter- current heat exchange
A_{Du}	Surface area of body
B	Heat exchange between each node and central blood pool
C_v	Specific heat at constant volume
C	Heat capacity of node (i, j)
C_d	Conductance between node and its neighboring layer
C_h	Shivering heat production
C	Concentration of a diffusive species,
d	Distance to the closest wall (m)
$\dot{d}$	Source terms of diffusive species. (1/sec)
D	Heat transmitted by conduction to the neighboring layer within the same segment
D_m	Diffusion coefficient (m^2/sec)
E_{Req}	Required rate of evaporation of Sweat from skin to compensate the skin heating
E_{Max}	Maximum possible sweat evaporation from skin
$E(i, 4)$	Evaporative heat loss at skin
$E_b(i, 4)$	Heat loss due to water vapor diffusion through the skin
e	Water vapor pressure (kPa)
f_{CL}	Clothing area factor
f_{v1}	Damping function

Symbol	Meaning
f_t	Empirical function in turbulence model is S-A model
f_w	Empirical function in turbulence model is S-A model
g_i	Acceleration due to gravity (m/s ²)
h_e	Evaporative heat transfer coefficient from skin to environment
h_t	Total heat transfer coefficient from skin surface to environment
h_r	Radiant heat transfer coefficient
h_c	Convective heat transfer factor
i	Body segment number
I_{CL}	Clothing insulation
j	Layer number in segment
k	Turbulent Kinetic Energy (J)
k	Thermal Conductivity (W.m /K)
K	Von- Karman constant
l_m	Mixing-length (m)
L_s	Length scale (m)
met	Metabolic rate of whole body
$Metf$	Distribution coefficient of individual muscle layer for heat production by external work
p	Pressure (N/m ²)
P_k	Rate of production in transport equation
$p_a(1)$	Vapor pressure at head segment
p_a	Ambient vapor pressure
p_{SK}	Saturated vapor pressure at skin surface

Symbol	Meaning
q	Heat flux (kJ/m ² sec)
Q	Rate of heat production
Q_b	Basal metabolic rate
Q_t	Sensible heat exchange between skin surface and environment
$RES(i, 1)$	Heat lost by respiration at chest section
$\tilde{S}$	Intermediate variables
S	Magnitude of Vorticity
S_{ij}	Mean Strain
T	Temperature (°C)
t	Time (sec)
T_a	Dry bulb temperature
$t_a(1)$	Temperature of head segment
t_o	Operating temperature
T_d	Dry-bulb temperature (°C)
T_w	Wet-bulb temperature (°C)
T_g	Black-global temperature (°C)
T_{amb}	Ambient Air Temperature (°C)
u	Velocity in x direction (m/s)
$\hat{u}$	Unit velocity vector in x- direction (m/s)
U	Mean velocity in x- direction (m/s)
u', v', w'	Fluctuating component of velocity (m/s)
$\bar{u}, \bar{v}, \bar{w}$	Time averaged component of velocity in x- direction (m/s)
v	Velocity in y direction (m/s)

Symbol	Meaning
ν	Molecular kinematic viscosity
$\tilde{\nu}$	Modified turbulent viscosity
V_s	Models mean flow velocity (m/s)
w	Velocity in z direction (m/s)
W	Heat production by external work
ws	Wind speed at an elevation of 10m (m/s)
β	Thermal expansion coefficient (1/k)
ρ	Density (kg/m ³)
ρC	Volumetric specific heat of blood
μ	Dynamics Viscosity (N.s/ m ²)
μ_t	Eddy viscosity (N.s/ m ²)
δ_{ij}	Kronecker delta
σ	Turbulent Prandtl number
ε	Turbulent dissipation rate
τ	Stress (N/m ²)
Ω_{ij}	Rotational tensor
Φ	Viscous dissipation function
∇	Gradient Operator
η	Numerical Constant
ω	Specific rate of dissipation of turbulent kinetic energy

ACRONYMS

Abbreviation	Meaning
ABS	Acrylonitrile Butadiene Styrene
AT	Apparent Temperature
BIS	Bureau Of Indian Standard
BMI	Body Mass Index
BF	Blood Flow Rate
BFB	Basal Blood Flow Rate
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CSF	Cerebral Spinal Fluid
FEM	Finite Element Modelling
FVM	Finite Volume Method
GRP	Glass Reinforced Plastics
HIC	Head Injury Criterion
JOS	JOint System
PDE	Partial Differential Equations
PTW	Powered Two Wheeler
RANS	Reynolds Averaged Navier-Stokes Equations
RH	Relative Humidity
RMS	Root Mean Square
RNG	Re-Normalization Group
TBI	Traumatic Brian Injuries
WBGT	Wet Bulb Global Temperature