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

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INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

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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.*

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(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^{o}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^{o}C. In temperature range of 36^{o}C to 38^{o}C, 81% riders found ventilated helmets comfortable and only 19 % riders found ventilated helmet comfortable beyond 38^{o}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 अत्यअधिक पसीने के कारण मोटरसाइकिल सवार हेलमेट पहनने में परेशानी तथा अनिच्छा अनुभव करते हैं | हेलमेट में सुराख़ 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 हैं । कम्प्यूटेशनल फ्लूड डायनामिक्स (सीएफडी) सिमुलेशन के परिणाम से यह भविष्यावाणी करने में मदद मिलेगी की मोटरसाइकिल सवार को सुराख़दार 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 हैं की, क्या सुराख़ करने से हेलमेट की सुरक्षा प्रदान करने की क्षमता प्रभावित तो नहीं हुई हैं ? 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 हैं | 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 उल्लखित प्रयोगिक व्वयस्था के लिए यह पाया गया है कि सपलार्ट - अलमर्स (Spalart - Allmaras) मॉडल, के - एप्सिलोन $(k - \varepsilon)$ मॉडल से प्रवाह मानकों की बेहतर भविष्यवाणी करता हैं | 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, सुराख़दार हेलमेट बनाये गए, जिन पर वायु प्रवाह सिमुलेश 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 (सपोर्टस) की समुचित संख्या निर्धारित करने के लिए भी हवा के प्रवाह के सिमुलेशन के परिणामों का उपयोग किया गया हैं |

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 हैं | 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 अध्यन भी शामिल है | संख्यात्मक परिणामो को औसत तापमान, स्पष्ट तापमान और गीला बल्ब वैश्विक तापमान (WBGT) के अनुसार प्रस्तुत किया गया हैं | संख्यात्मक परिणाम यह सुझाव देते है कि $36^{o}C$ 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 परिणामो 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 (एक्सीलेरेशन) 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। परिणामो से यह संकेत मिलता है कि हवादार हेलमेट भारतीय मानक ब्यूरो

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

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

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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 (^{o}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 (^{o}C)
T_w	Wet-bulb temperature (^{o}C)
T_g	Black-global temperature (^{o}C)
T_{amb}	Ambient Air Temperature (^{o}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
v	Molecular kinematic viscosity
$\tilde{v}$	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