CFD Analysis of Temperature Distribution and Thermal Comfort of Complete Footwear for Hot and Cold Country

Abu Jor¹, Md. Rafiul Hashar², Md. Samsul Arefin³,a)

¹,²,³Department of Leather Engineering, Khulna University of Engineering & Technology, Khulna-9203, BANGLADESH

a)Corresponding author: arefinkuet@gmail.com, arefin@le.kuet.ac.bd

Abstract. Computational fluid dynamics (CFD) has become an elemental tool for analyzing various phenomena of footwear comfort nature during wear like temperature distribution and velocity magnitude within the footwear and find out its thermal comfort level. The goals of this study were to analyze the temperature distribution and the level of thermal comfort for complete footwear during wear through predicted mean vote (PMV) & percentage person’s dissatisfaction (PPD) model by using CFD techniques. This makes establishing heat transfer-thermal-comfort relationships easier to approximate. For this analysis, environmental conditions of cold (-20°C) and hot (50°C) countries were considered and also considered the upper materials as leather. The occupant (human foot) felt neutral to slightly cool in the cold country and felt very hot in the hot country within the footwear and their PPD is more than 25% and 99.1% respectively that means 75% persons will be satisfied in the cold country and only of 0.99% persons will be satisfied in the hot country. Thus the effectiveness of the footwear design for keeping the human foot comfortable for any kind of design and region can be assessed.

INTRODUCTION

Nowadays, the footwear and textile manufacturers are focused not only on the quality and design of their products, but also on customer comfort, which has also been one of the primary functions of most of textile products [1]. The climate inside a shoe is controlled by thermal and moisture conditions and is important to attain comfort. Development of thermal models that are capable of predicting in-shoe temperature distributions is an effective way forward to undertake extensive parametric studies to assist optimized design [2]. Regarding foot comfort, the movement adaptability of the material, waterproof qualities, weight and the thermal as well as moisture control would be the main parameters to be taken into account during footwear design & development [3]. According to the inquiry performed by Kuklane et al. [4] about the main problems related to feet comfort, up to 43% of customers dislike having cold feet and 12% are concerned about sweat problems. Therefore, thermal comfort is an important key when considering comfortable footwear, and it can be achieved by keeping the footwear temperature in the range from 27 °C to 33°C [3, 5]. The aims of this study were to investigate the temperature distribution across the footwear during wear using CFD technique and analyzed their thermal comfort level using PMV and PPD model for cold and hot country perspective.

MATHEMATICAL FORMULATION

The commercial code Autodesk® Simulation CFD 2015 was used to simulate a three-dimensional steady state turbulent flow and heat transfer in the computational model. The partial differential equations governing fluid flow and heat transfer include the continuity equation, the Navier-Stokes equations and the energy equation [6]. A continuity equation describes the transport of a conserved quantity. The continuity equation is given below:

\[
\frac{\partial u}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} + \frac{\partial u}{\partial z} = 0
\]  

(1)

Navier-Stokes equations are the basic governing equations for a viscous, heat conducting fluid. The Navier-Stokes equations are given below:
\[
\rho \left( \frac{\partial v}{\partial t} + v \nabla v \right) = -\nabla p + \mu \nabla^2 v + f
\]

(2)

For incompressible and subsonic compressible flow, the energy equation is written in terms of static temperature:
\[
\rho C_p \left( \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = \frac{\partial}{\partial x} \left[ k \frac{\partial T}{\partial x} \right] + \frac{\partial}{\partial y} \left[ k \frac{\partial T}{\partial y} \right] + \frac{\partial}{\partial z} \left[ k \frac{\partial T}{\partial z} \right] + q_v
\]

(3)

**MATERIAL PROPERTIES**

The material properties required for a transient heat transfer footwear model include mass density, specific heat, thermal conductivity, emissivity, transmissivity, electrical resistivity and wall roughness; a list of the material properties used in the heat transfer footwear models and their sources can be seen in Table 1.

<table>
<thead>
<tr>
<th>Model part</th>
<th>Thermal conductivity (W/m-k)</th>
<th>Specific heat (J/Kg-K)</th>
<th>Mass density (Kg/m^3)</th>
<th>Emissivity</th>
<th>Transmissivity</th>
<th>Electrical resistivity (ohm-cm)</th>
<th>Wall roughness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insole (particle board)[^13]</td>
<td>0.078</td>
<td>1300</td>
<td>590</td>
<td>0.8</td>
<td>0</td>
<td>3e+17</td>
<td>0</td>
</tr>
<tr>
<td>Occupant (human foot)[^13]</td>
<td>50</td>
<td>4182</td>
<td>998</td>
<td>0.98</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Air volume[^13]</td>
<td>0.02563</td>
<td>1004</td>
<td>--</td>
<td>1</td>
<td>--</td>
<td>--</td>
<td>0</td>
</tr>
</tbody>
</table>

These properties are also only of importance in transient models, where the change in temperature with respect to time is not zero. The thermal property that defines the contact between materials determines the continuity of temperature distributions and the degree of heat flow between separate materials.

**IMPLEMENTATION OF THE SIMULATION MODEL**

For this analysis considered two different temperature regions such as cold and hot country temperatures and also considered the upper material as leather. The process is done by generating a geometric model and specifying material properties along with boundary conditions. Next, the model is divided into smaller elements connected at nodes through a process known as meshing and then solved the model (Fig. 1). Finally, plots and numerical results are output to provide engineers with insights to the behavior of the model. All the boundary conditions have been assigned for cold country temperature (-20°C) [^14] and hot country temperature (50°C) [^15].
A 3D footwear model with human foot inside it was modeled for this study using solid works software. Table 2 represents the detail dimensions of the model. Leather was assigned as upper materials, taxon/particle board as insole, human material as foot and air was assigned to internal gap. By assigning boundary conditions such as heat flux, heat generation, film coefficient, velocity, pressure and temperature to the openings and other specific locations of a complete footwear, it was effectively "connected" the design with the physical world. Air velocity was assigned at the inlet surface of 0.15 m/s [16] to flow air inside the footwear and a temperature of about -20°C and 50°C was assigned at the inlet section respectively for cold and hot country weather. The outlet surface was defined with atmospheric pressure which allowed the air to move within model boundary. To simulate heat transfer to the surroundings, a film coefficient boundary condition was applied to the external surfaces.

![Diagram of simulation model](image.png)

**Fig. 1. Implementation of the simulation model**

Considering the surrounding air is still, a film coefficient value of 5 W/m² K was used [17]. Reference temperature for film coefficient was equal to ambient temperature of the respective areas which was of around -20°C and 50°C respectively. Heat flux put into the system to represent the heat provided by blood flow. To consider the value of heat flux in CFD simulation, heat flux boundary condition was used on the surface of the human foot model. The value for the heat flux was taken from estimated whole body values of walking (at1.3 m/s) 150 W/m² as presented by cengel [18]. Here the foot surface area was about 7 percent of the whole body surface area.

<table>
<thead>
<tr>
<th>Shoe Dimension</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>43</td>
</tr>
</tbody>
</table>

Table 2. Detail dimensions of the CAD model
Prior to running an Autodesk Simulation CFD analysis, the geometry is broken up into small pieces called elements. The corner of each element is a node. The calculation is performed at the nodes. These elements and nodes make up the mesh. The solution accuracy of any simulation largely depends on grid generation. Automatic mesh scheme followed by advanced mesh enhancement was used to generate fine mesh (Fig.2).

Fig. 2. Meshing view of the CAD model

To define how the simulation runs, the physics tab was used to enable physical models such as flow and heat transfer, the control tab to specify analysis parameters such as steady state or transient and to set the number of iterations and the adaptation tab was used to progressively improve the mesh by running the simulation multiple times. At the end of each run, Adaptation modifies the mesh based on the results, and uses the new mesh for the next cycle. The result is a mesh that is optimized for the particular simulation. Table 3 represents the solver settings.

<table>
<thead>
<tr>
<th>Solution parameters</th>
<th>Settings/Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
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</table>

Table 3. Solver settings
RESULTS AND DISCUSSION

Fig. 3. Temperature distribution cut plane (a) for hot country (50°C) and (b) for cold country (-20°C) temperature

Assigned air of -20°C and 50°C temperature entered into the footwear and came in contact with the heat generating source (i.e. human foot) and got heated (Fig. 3). In this way temperature was distributed inside the footwear and increased due to the insulating property of footwear and remained between 11.1°C to 12.3°C and 51°C to 53.3°C respectively. In figure 3(a) continuous air flow from the opening of the footwear but in figure 3(b) no air flows within the footwear resulting from the close air tight opening of the footwear during wear in cold country.
The temperature profile at the toe, heel and bottom portion on XY plane (Fig. 4) in case of cold country. It showed the vertical thermal stratification in the footwear. At the toe, heel and bottom portion the temperature was in the range of 11.50°C to 11.51°C, 11.20°C to 11.30°C and 11.32°C to 11.50°C respectively. The temperatures within the footwear were near the same in the entire toe, heel and bottom portion because of close air tight opening of the footwear and unavailability of air circulation. In the same way, the temperature profile at the toe, heel and bottom portion on XY plane (Fig. 5) in case of hot country. At the toe, heel and bottom portion the temperature was in the range of 52.85°C to 53.3°C, 50.6°C to 51.2°C and 51.2°C to 53.3°C respectively whereas optimum and acceptable ranges of operative temperature for people during 50% relative humidity and mean air speed (≤ 0.15 m/s) are 22°C and 24.5°C according to ASHRAE [19]. The intensity of temperature within the footwear was much more at the toe portion than in the heel portion results due to the variation of air circulation at the opening of the footwear.
Fig. 6. Comparison of (a) PMV and (b) PPD among two different temperature regions

According to PMV, the occupant (human foot) felt very hot in the hot country, neutral to slightly cool in the cold country within the footwear according to ASHRAE thermal sensation scale (Table 4) and their PPD is up to 99.1% in hot country but up to 24% in cold country temperature (Fig. 6), whereas the acceptable thermal environment for general comfort are PMV, -0.5 to +0.5 and PPD, <10% [20] that means the footwear is near the comfort range only in cold country regions with closed air tight at the opening of the footwear.

<table>
<thead>
<tr>
<th>Value</th>
<th>Sensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>+3</td>
<td>Hot</td>
</tr>
<tr>
<td>+2</td>
<td>Warm</td>
</tr>
<tr>
<td>+1</td>
<td>Slightly warm</td>
</tr>
<tr>
<td>0</td>
<td>Neutral</td>
</tr>
<tr>
<td>-1</td>
<td>Slightly cool</td>
</tr>
<tr>
<td>-2</td>
<td>Cool</td>
</tr>
<tr>
<td>-3</td>
<td>Cold</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

A simple 3D model has been developed successfully to simulate in-footwear temperatures in various locations using CFD simulation. These models covered two different temperature regions as boundary conditions. Predicted temperature distributions in the foot and shoe indicate greater heat transfer in the toe region in case of hot country but in the cold region temperatures were increased and distributed evenly. This model demonstrated a powerful approach to simulating in-footwear microclimate conditions, with promising results. The modeling results were then linked to the thermal comfort index to assist footwear manufacturers to design footwear with better thermal comfort. Occupant’s (human foot) PMV and PPD values were not acceptable according to ASHRAE thermal sensation scale when used in hot country temperature due to felt hot in this
region. Because of very high temperature around the human foot experienced approximately 99.1% discomfort in this region. On the other hand PMV and PPD values were quite acceptable when the footwear was used in cold country temperature; hence the human foot felt neutral to slightly cool in this region according to ASHRAE thermal sensation scale. Here the human foot experienced only 25% discomfort which showed good option according to the foot comfort range. Now it can be conclude that the designed footwear model is comparatively best for use in cold country. This work will establish a base to develop more complex 3D thermal models, further to the coupled models, to cover both temperature and moisture. The techniques developed are also useful for modeling other microclimate conditions, such as in-glove, helmet and in-clothing environments.

REFERENCES

[10] D Brownleigh, Raleigh, Basics of non-contact temperature measurement, MICRO-EPSILON, 8120, NC 27617 / USA.