

## Temperature Distribution and Thermal Comfort Analysis of a Shoe for summer and Winter Season Using CFD Technique: Bangladesh Perspective

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### Abstract

*This paper reports a computational fluid dynamics (CFD) analysis in a shoe during wear, under controlled conditions. Simulation of footwear is becoming very popular in recent years for effective shoe designing through heat transfer, heat generation, heat flux etc. analysis. The aims of this study were to analyze the temperature distribution and thermal comfort level of shoes through predicted mean vote (PMV) & percentage person's dissatisfaction (PPD) model by using CFD technique. For this analysis two different temperature seasons such as summer (40°C) and winter (7°C) season of Bangladesh were considered. According to the PMV scale, the human foot felt hot in the summer season and neutral to slightly cool in the winter season within this shoe and their PPD is up to 99.1% and 24% respectively. Thus, from this analysis it can be conclude that the designed shoe model is comparatively best for use in winter season of Bangladesh.*

Keywords: CFD, footwear, temperature, comfort, simulation.

### 1. Introduction

Thermal comfort is increasingly becoming a crucial factor to be considered in shoe design. The climate inside a shoe is controlled by thermal and moisture conditions and is important to attain comfort. Research undertaken has shown that thermal conditions play a dominant role in shoe climate. 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 [1]. 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 and leather products [2]. Regarding foot comfort, the movement adaptability of the material, waterproof qualities, weight and the thermal and moisture control would be the main parameters to be taken into account in shoe 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 shoes, and it can be achieved by keeping the shoe temperature in the range from 27°C to 33°C [3, 5]. Besides that, according to Covill et al. [6], the amount of heat generated or supplied to the feet must be compensated by heat loss, so the rate of heat generation and release must be similar in order to maintain the temperature in the comfort range. In addition, the heat flux released by the feet could reach values up to 150 W/m<sup>2</sup> during walking and 240 W/m<sup>2</sup> during exercise [3]. In this study, investigate the temperature distribution within the shoe during wear using CFD technique and analyzed their thermal comfort level using PMV and PPD model according to ASHRAE standard [7].

### 2. 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 [8]. A continuity equation ' (1) ' describes the transport of a conserved quantity. Since mass, energy, momentum, electric charge and other natural quantities are conserved under their respective appropriate conditions; a variety of physical phenomena may be described using continuity equations. The continuity equation is given below:

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$$\frac{\partial u}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} + \frac{\partial u}{\partial z} = 0 \quad (1)$$

Navier-Stokes equation ' (2) ' is the basic governing equations for a viscous, heat conducting fluid. The Navier-Stokes equations are given below:

$$\rho \left( \frac{\partial v}{\partial t} + v \cdot \nabla v \right) = -\nabla p + \mu \nabla^2 v + f \quad (2)$$

For incompressible and subsonic compressible flow, the energy equation ' (3) ' is written in terms of static temperature:

$$\rho C_p \left( \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = \frac{\partial}{\partial x} \left[ k \frac{\partial T}{\partial x} \right] + \frac{\partial}{\partial x} \left[ k \frac{\partial T}{\partial x} \right] + \frac{\partial}{\partial x} \left[ k \frac{\partial T}{\partial x} \right] + qv \quad (3)$$

### 3. Material properties

The material properties required for a transient heat transfer shoe model include mass density, specific heat, thermal conductivity, emissivity, transmissivity, electrical resistivity and wall roughness. These properties are also only of importance in transient models, where the change in temperature with respect to time is not zero. The models in this study predominantly used values for these properties that were given in the literature; a list of the material properties used in the heat transfer footwear models and their sources can be seen in Table 1. The thermal property that defines the contact between materials, determines the continuity of temperature distributions and the degree of heat flow between separate materials.

**Table 1.** Material properties used to assign the CAD model for simulation

Model part	Thermal conductivity (W/m-k)	Specific heat (J/Kg-K)	Mass density (Kg/m <sup>3</sup> )	Emissivity	Transmissivity	Electrical resistivity (ohm-cm)	Wall roughness (mm)
Shoe upper (leather)	0.16 <sup>[9]</sup>	1500 <sup>[10]</sup>	998 <sup>[11]</sup>	0.95 <sup>[12]</sup>	0.02 <sup>[12]</sup>	1e+16 <sup>[13]</sup>	0.000874 <sup>[14]</sup>
Insole (particle board) <sup>[15]</sup>	0.078	1300	590	0.8	0	3e+17	0
Occupant (human foot) <sup>[15]</sup>	50	4182	998	0.98	0	0	0
Air volume <sup>[15]</sup>	0.02563	1004	--	1	--	--	0

### 4. Implementation of the simulation model

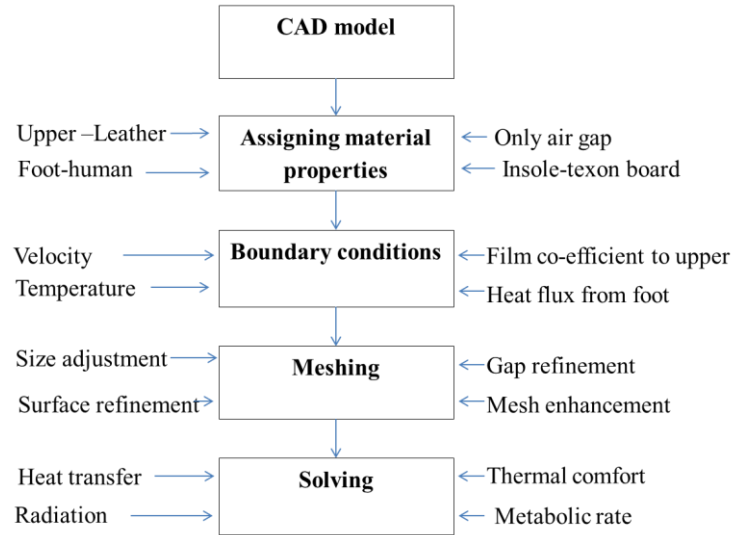
For this analysis considered two different temperature seasons such as summer and winter season of Bangladesh and also considered the upper material as leather. The process shown in figure 1 was done by generating a geometric model and specifying material properties along with boundary conditions. Next, the model is divided into smaller elements connected at nodes through a process known as meshing and then solved the model. 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 winter season temperature (7°C) and summer season temperature (40°C) of Bangladesh [16].

#### CAD model

A 3D footwear model with human foot inside it was modeled for this study using CAD software. The detail dimensions of the model can be seen in Table 2.

#### Materials assignment

Analysis of footwear with Autodesk Simulation CFD relies on the proper assignment of fluid, solid, and occupant materials. It was assigned with leather materials to upper, taxon board to insole, human to foot and air to internal gap.



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

### Boundary conditions

By assigning boundary conditions such as heat flux, heat generation, film coefficient, velocity, pressure and temperature to openings and other specific locations, we wear effectively "connected" the design with the physical world. Air velocity was assigned at the inlet surface of 0.15 m/s to flow air inside the shoe and a temperature of about 7°C and 40°C was assigned at the inlet section respectively for winter and summer season of Bangladesh.

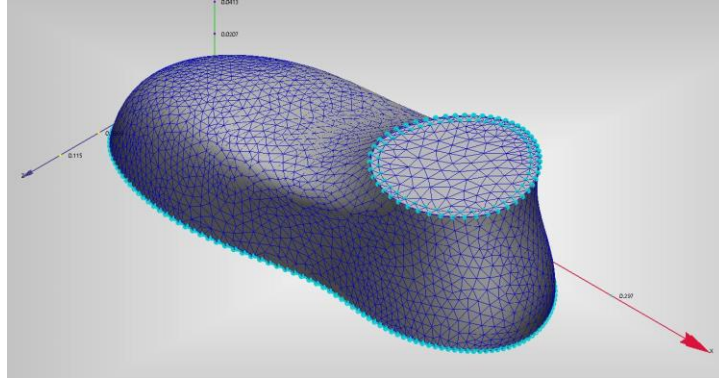
The outlet surface was defined with atmospheric pressure which allowed the air to move within the model boundary. To simulate heat transfer to the surroundings, without actually modeling the surrounding environment, a boundary condition of film coefficient was applied to the external surfaces. Considering the surrounding air is still, a film coefficient value of 5 W/m<sup>2</sup> K was used. Reference temperature for film coefficient was equal to ambient temperature of the respective areas which is of around 7°C and 40°C respectively. Heat flux put into the system to represent the heat provided by blood flow. For considering heat flux components in simulation CFD, boundary condition of heat flux was used on the surface of the human foot model. The value for the heat flux wear taken from estimated whole body values of walking (at 1.3 m/s) 150 W/m<sup>2</sup> as presented by cengel. Here the foot surface area was about 7 percent of the whole body surface area [17].

### Meshing

The geometry is broken up into small pieces prior to running an Autodesk CFD simulation 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. In figure 2, automatic mesh scheme followed by advanced mesh enhancement was used to generate fine mesh.

**Table 2.** Detail dimensions of the CAD model

Shoe	Dimension	Unit
Size	43	Paris point
length	28.66	cm
width	9.25	cm
Upper(leather) thickness	0.08	cm
Insole(particle board) thickness	0.20	cm



**Fig.2.** Meshing view of the CAD model

### Solving

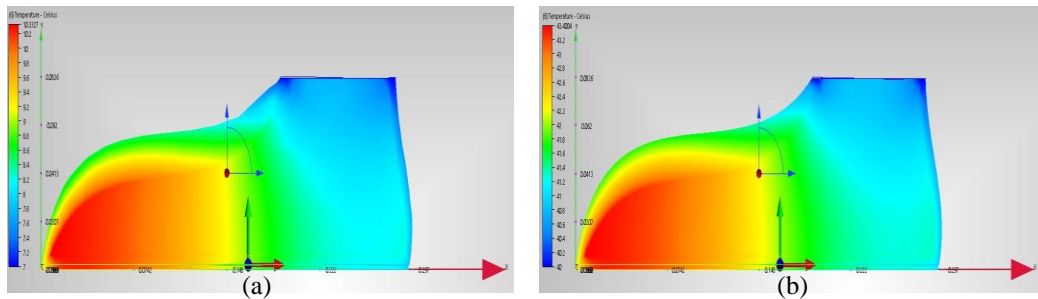
The settings to solve the simulation are in table 3. To define how the simulation runs, solve quick edit dialog contains three tabs. The physics tab was used to enable physical models such as flow and heat transfer, the control tab to specify analysis parameters such as steady state or transient and 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 modified the mesh based on the results and used the new mesh for the next cycle. The result is a mesh that is optimized for the particular simulation. The mesh is finer for high gradient regions and coarser elsewhere.

**Table 3.** Solver settings

Solution parameters	Settings/Values
Heat transfer	On
Radiation	On
Thermal comfort	On
Metabolic rate	150 W/m <sup>2</sup>
Humidity	50%
Clothing(socks)	0.74 clo
Iterations run	100

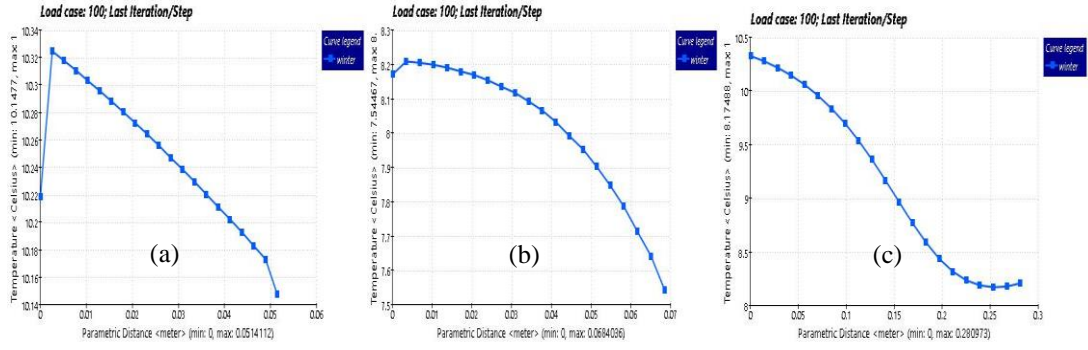
## 5. Results and Discussions

Assigned air of 7°C and 40°C entered into the shoe and came in contact with the heat generating source (i.e. human foot) and got heated. In this way temperature was distributed inside the shoe and increased due to the insulating property of shoe and remained between 8.2°C to 10.3°C and 41.2 to 43.4°C respectively shown in figure 3.

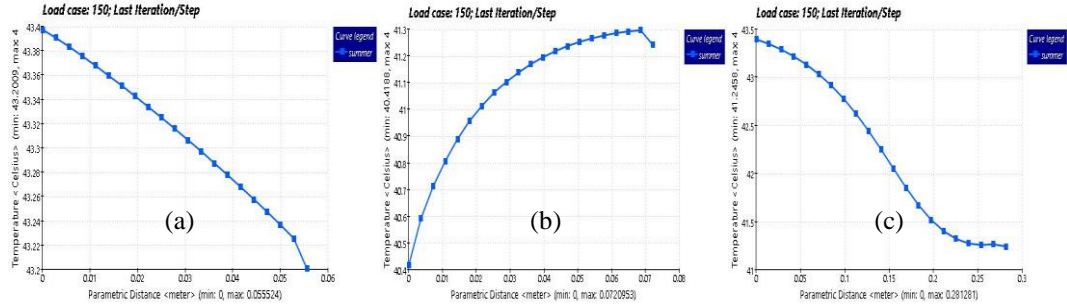


**Fig. 3.** Temperature distribution (a) for winter and (b) for summer season of Bangladesh

The temperature profile at toe, heel and bottom portion on XY plane was shown in figure 4 for winter season of Bangladesh. It showed the vertical thermal stratification in the shoe. At the toe, heel and bottom portion the temperature was in the range of 10.15°C to 10.34°C, 7.6°C to 8.2°C and 8.2°C to 10.3°C - respectively. In the -



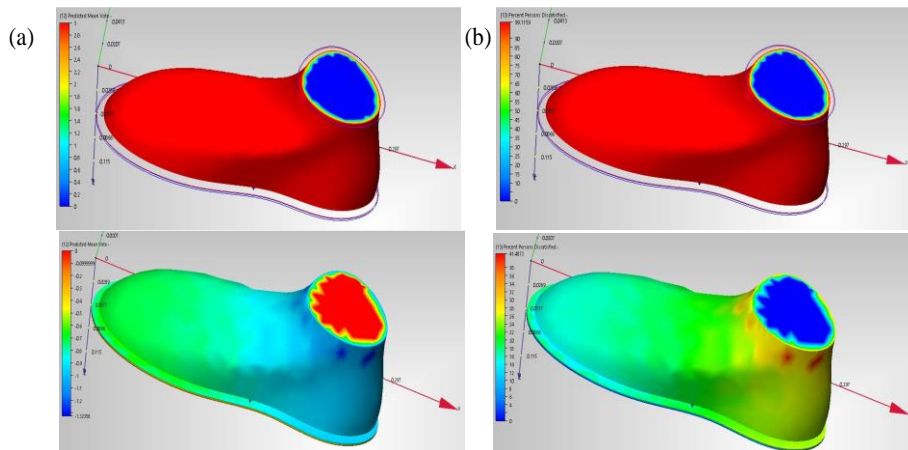
**Fig. 4.** Temperature profile at (a) toe portion, (b) heel portion and (c) bottom portion for winter season of Bangladesh



**Fig. 5.** Temperature profile at (a) toe portion, (b) heel portion, (c) bottom portion in summer season of Bangladesh

same way, the temperature profile at toe, heel and bottom portion on XY plane was shown in figure 5 for summer season of Bangladesh. At the toe, heel and bottom portion the temperature was in the range of 43.2°C to 43.4°C, 40.4°C to 41.3°C and 41.3°C to 43.4°C respectively in summer season of Bangladesh whereas optimum and acceptable ranges of operative temperature for people during 50% relative humidity and mean air speed ( $\leq 0.15$  m/s) are 22°C and 24.5°C for winter and summer respectively according to ASHRAE [18]. The temperatures within the footwear were much more in the toe portion than in the heel portion due to the variation of air circulation within the shoe.

According to PMV, the occupant (human foot) felt neutral to slightly cool in the winter season and felt hot in the summer season of Bangladesh within the shoe and their PPD is up to 99.1% in summer season but up to 24% in winter season of Bangladesh shown in figure 6, that means the shoe is near the comfort range only in winter season of Bangladesh whereas the acceptable thermal environment for general comfort are PMV, -0.5 to + 0.5 and PPD, <10% [19].



**Fig. 6.** Comparison of (a) PMV and (b) PPD among two different temperature regions

## 6. Conclusions

In this research work, thermal comfort aspects of shoe were analyzed for two different temperature seasons such as winter season and summer season of Bangladesh using CFD simulation technique. The main goals of this study were to investigate the temperature distribution inside the shoe and analyze their thermal comfort level and find out a way of verifying optimum comfort for shoe design. The temperatures within the footwear were much more in the toe portion than in the heel portion due to the variation of air circulation within the shoe. Occupant's (human foot) PMV and PPD values were not acceptable according to ASHRAE thermal sensation scale when used in summer season of Bangladesh due to human foot felt hot and experienced 99.1% discomfort in this season. On the other hand PMV and PPD values were quite acceptable when the shoe used in winter season of Bangladesh due to the human foot felt neutral to slightly cool and experienced only 24% discomfort which showed a good accordance with the comfort range. Now it can be conclude that the designed shoe model is comparatively best for use in winter season of Bangladesh. Thus the effectiveness of the shoe design for keeping the human foot comfortable for any kind of design or temperature regions can be assessed. Thus can be analyzed the effects of design changes and develop a design that delivers the desired performance.

## 7. Acknowledgement

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