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Study of Thermal Distribution and Comfort in Shoe through CFD Technique

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Abstract- Thermal comfort is an essential element for the human body and is increasingly becoming a crucial factor to be considered in footwear design. The previous study 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 to assist in design optimization. The aim of this study was to analyse the distribution of temperature, and the level of thermal comfort during wear of footwear through predicted mean vote (PMV) & percentage person's dissatisfaction (PPD) model using computational fluid dynamics (CFD) techniques. These will make easier to approximate the heat transferthermal-comfort relationships among the components. Four different temperatures ranges from very cold to very hot such as -20°C, 7°C,40°C,50°C were considered for this analysis,. The occupant (human foot) felt neutral to slightly cool in the cold weather and felt very hot in the hot weather within the footwear, and their PPD is more than 25%, 24%, 99.1%, and 99.1% respectively that means 74-75% persons will be satisfied in the cold and only of 0.99% persons will be satisfied in the hot country. Thus from this study, it can be concluded that the effectiveness of the footwear design for keeping the human foot thermally comfortable for different variety of weather can be assessed through this technique of CFD simulation.

Keywords: *CFD; footwear; temperature; comfort; simulation;*

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STUDYOFTHERMALDISTRIBUTIONANDCOMFORTINSHOETHROUGHCFDTECHNIQUE

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Study of Thermal Distribution and Comfort in Shoe through CFD Technique

Abu Jor [α], Md. Rafiul Hashar [σ] & Md. Samsul Arefin [ρ]

Abstract- Thermal comfort is an essential element for the human body and is increasingly becoming a crucial factor to be considered in footwear design. The previous study 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 to assist in design optimization. The aim of this study was to analyse the distribution of temperature, and the level of thermal comfort during wear of footwear through predicted mean vote (PMV) & percentage person's dissatisfaction (PPD) model using computational fluid dynamics (CFD) techniques. These will make easier to approximate the heat transfer-thermal-comfort relationships among the components. Four different temperatures ranges from very cold to very hot such as -20°C, 7°C,40°C,50°C were considered for this analysis,. The occupant (human foot) felt neutral to slightly cool in the cold weather and felt very hot in the hot weather within the footwear, and their PPD is more than 25%, 24%, 99.1%, and 99.1% respectively that means 74-75% persons will be satisfied in the cold and only of 0.99% persons will be satisfied in the hot country. Thus from this study, it can be concluded that the effectiveness of the footwear design for keeping the human foot thermally comfortable for different variety of weather can be assessed through this technique of CFD simulation.

Keywords: CFD; footwear; temperature; comfort; simulation;

I. Introduction

Thermal comfort has a significant influence on the human body. Some factors affect human thermal comfort properties are clothing worn, climate condition, and physical activity (Layton, 2001). Several studies undertaken have shown that thermal conditions play a dominant role in-shoe climate. The climate inside a shoeis very much important to attain comfort and is controlled by thermal and moisture conditions (Covill et al., 2010). 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 the apparels (Sarier et al., 2012). The movement, adaptability of the material, waterproof qualities, and weight, thermal as well as moisture control would be the important parameters to be taken into consideration during the design and development of comfortable footwear (Kuklane, 2009). Regarding feet comfort up to 43% of customers dislike having cold feet, and 12% are concerned about sweat problems [Kuklane et al., 1999]. Therefore, thermal comfort is a key demand when considering comfortable footwear, and it can be achieved by keeping the footwear in the range of temperature from 27 °C to 33°C (Kuklane, 2009, Song, 2008). Applications of CFD for airflow predictions and temperature distribution in footwear may become an effective approach. Nielsen et al. (1974) were one of the first to investigate airflow and heat transfer in a room of a building using a CFD technique. Many research articles on CFD modeling in the building systems have become available (Chiang et al., 2012). Ravikumar et al., (2009) assessed the predicted mean vote (PMV) at the mid-plane of the room to locate the thermally comfortable zone using CFD method. The goal of this analysis was to investigate the thermal distribution across the footwear during wear using CFD technique, to analyse their thermal comfort level using PMV and PPD model for different weather condition and to develop an approach for comfort study.

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II. Finite Element 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 [Sert, 2013]. A variety of physical phenomena like mass, energy, momentum, electric charge and other natural quantities may be described using continuity equations [Shukla et al., 2016]. The continuity equation is given below:

$$\partial u/\partial t + \partial u/\partial x + \partial u/\partial y + \partial u/\partial z = 0 \qquad (1)$$

Navier-Stokes equations are the basic governing equations for a viscous, heat conducting fluid. The Navier-Strokes equations are given below:

$$\rho\,(\partial v/\partial t + v\cdot\nabla v) = -\nabla p + \mu\nabla 2\, v + f \qquad (2)$$

For incompressible and subsonic compressible flow, the energy equation is shown regarding static temperature:

$$\rho Cp\,(\,\partial T/\partial t + u\,\partial T/\partial x + v\,\partial T/\partial y + w\,\partial T/\partial z = \partial/\partial x\,[k\,\partial T/\partial x] + \partial/\partial x\,[k\;\partial T/\partial x] + \partial/\partial x\,[k\;\partial T/\partial x\,] + q \qquad (3)$$

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III. Material Specifications

The material specification 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 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^3)	Emis sivity	Transm issivity	Electrical resistivity (ohm-cm)	Wall rough-ness (mm)
Footwear upper (leather)	0.16 (Saha, 2014)	1500 (Kanay, 1955)	998 (Ishii et al., 2014)	0.77(Spaldinget al.,1983)	0.02(Spalding et al.,1983)	1e+16 (Weir, 1952)	0.000874 (Liu, 2008)
Insole (particle board)*	0.078	1300	590	0.8	0	3e+17	0
Occupant (human foot)*	50	4182	998	0.98	0	0	0
Air volume*	0.02563	1004	--	1	--	--	0

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.

IV. Process Implementation

For this analysis considered four different thermal conditions such as very cold, cold and hot and very hot temperatures and also considered the upper material as leather. The process is done by generating a geometric thermal 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 behaviour of the model. All the boundary conditions have been assigned for the above selected temperatures -20°C (Samant, 2014), 7°C, 40°C(Khanna et al., 1998)and (50°C) (Samant, 2014).

Table 2: Detail specifications 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

A 3D footwear model with simulated human foot inside it was modelled for this study using solid works software. Table 2 represents the detail specifications of the model. Leather as upper, taxon/particle board as a insole, human as foot and the air was assigned as the 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 footwear, it was effectively "connected" the design with the physical world. Air velocity at the inlet surface of 0.15 m/s (ANSI/ASHRAE Standard 55, 2004) to flow air inside the footwear and the temperature at the inlet section was assigned respectively for selected weather conditions. The outlet surface was defined by atmospheric pressure which allowed the air to move within the model boundary. A boundary condition of film coefficient was also applied to the external surfaces to simulate heat transfer to the surroundings.

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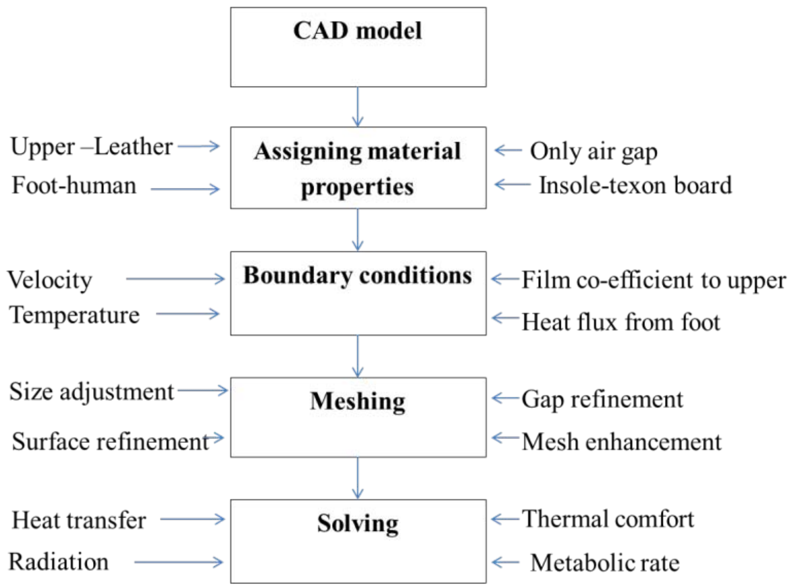

Figure 1: Implementation of the simulation model

Considering the surrounding air is static, a film coefficient value of 5 W/m² K was used (Autodesk, 2014). Reference temperature for film coefficient was equal to the ambient temperature of the respective areas which was of respectively around the assigned condition. Heat flux put into the system to represent the heat provided by blood flow. The boundary condition of heat flux was used on the surface of the human foot model to consider the value of heat flux in CFD simulation. The value of 150 W/m^2 (at1.3 m/s) was taken from the estimated whole body as the heat flux during walking (Cengel, 1998). Here the foot surface area covered about 7% of the total body surface area.

Before running an Autodesk Simulation CFD analysis, the geometry is broken up into small components 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).

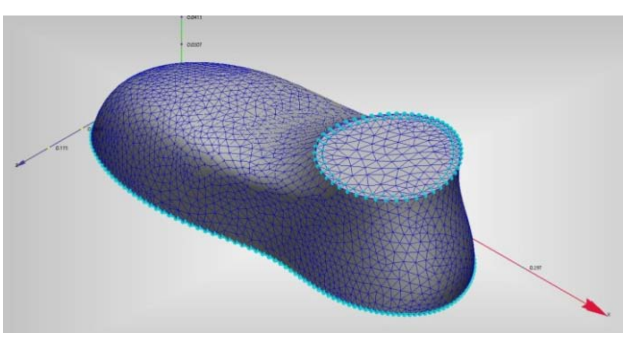

Figure 2: Meshing view of the CAD model

To define the simulation way, the physics tab 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 3: Solver settings

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

V. Results And Discussion

The assigned air of -20°C, 7°C, 40°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 it and remained between 11.1°C to 12.3°C, 8.2°C to 10.3°C, 41.2 to 43.4°C and 51°C to 53.3°C respectively.

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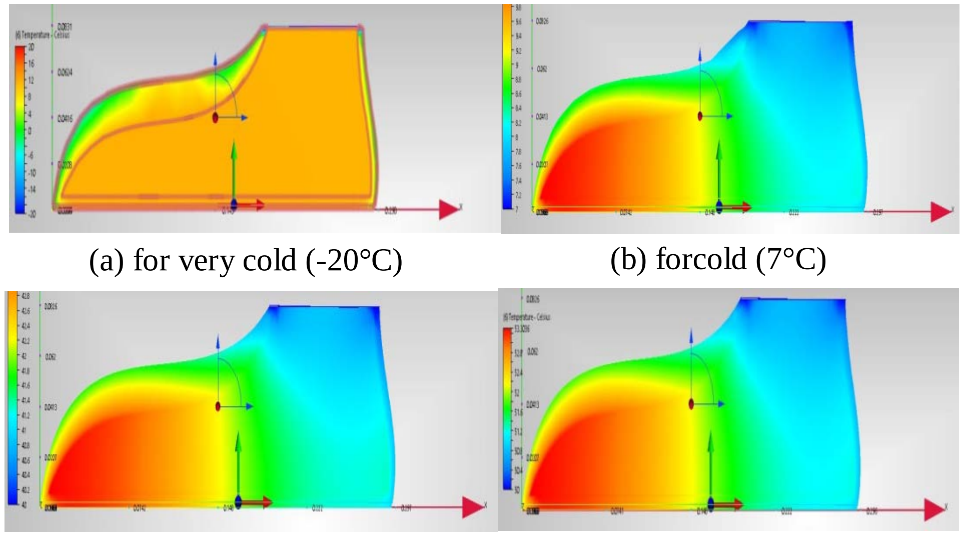


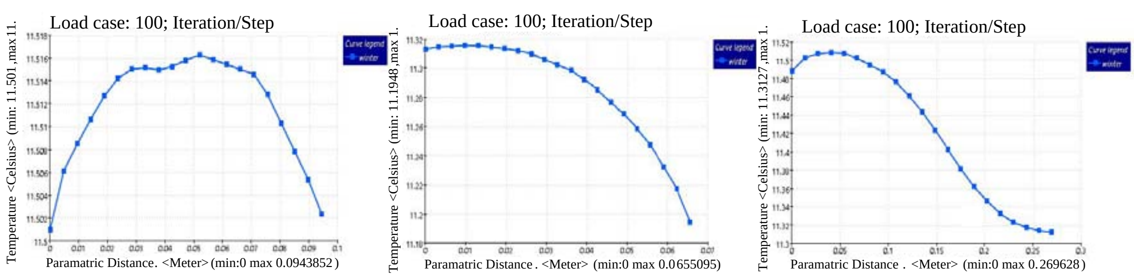
(a) for very cold (-20°C) (b) forcold (7°C)

(c) for hot (40°C) (d) for very hot (50°C)

Figure 3: The temperature distribution cut plane at different weather condition

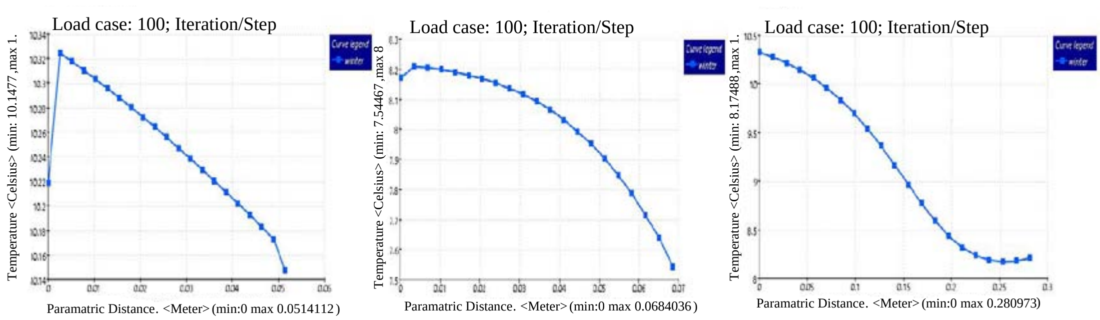
In figure 3(b) continuous air flow from the opening of the footwear but in figure 3(b) no air within it resulting from the close air tight opening of the footwear during wears in cold country.

The temperature profile at toe, heel and bottom portion on the XY plane in case of very much cold condition shown in Fig. 4. 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 compact air-tight opening and unavailability of air circulation. In the same way, the temperature profile at the toe, heel and bottom portion on XY plane in case of cold condition (Fig. 5) 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 case of hot weather condition (Fig. 6),it 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, and in case of very much hot condition (Fig. 7) 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.



(a) At toe portion (b) At heel portion (c) At bottom portion

Figure 4: The temperature profile in case of very cold (-20°C)weather



(a) At toe portion (b) At heel portion (c) At bottom portion

Figure 5: Thetemperature profile in case of cold (7°C) weather

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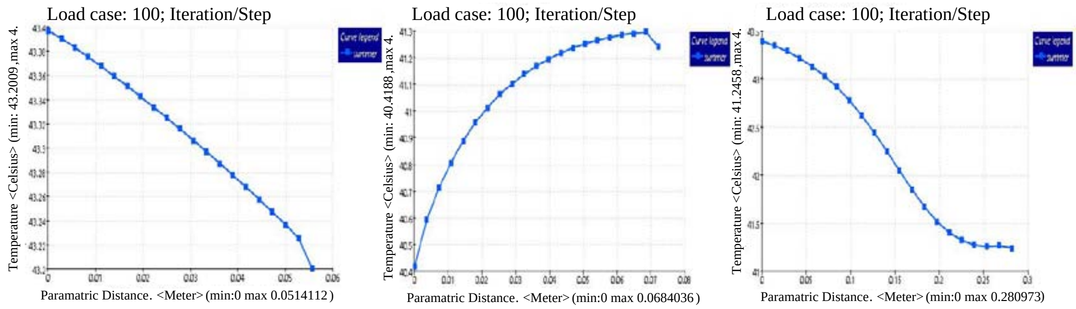
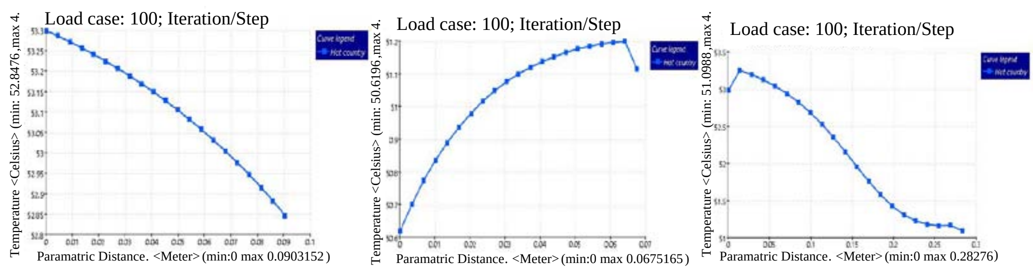


(a) At toe portion (b) At heel portion (c) At bottom portion

Figure 6: Thetemperature profile in case of hot (40°C) weather

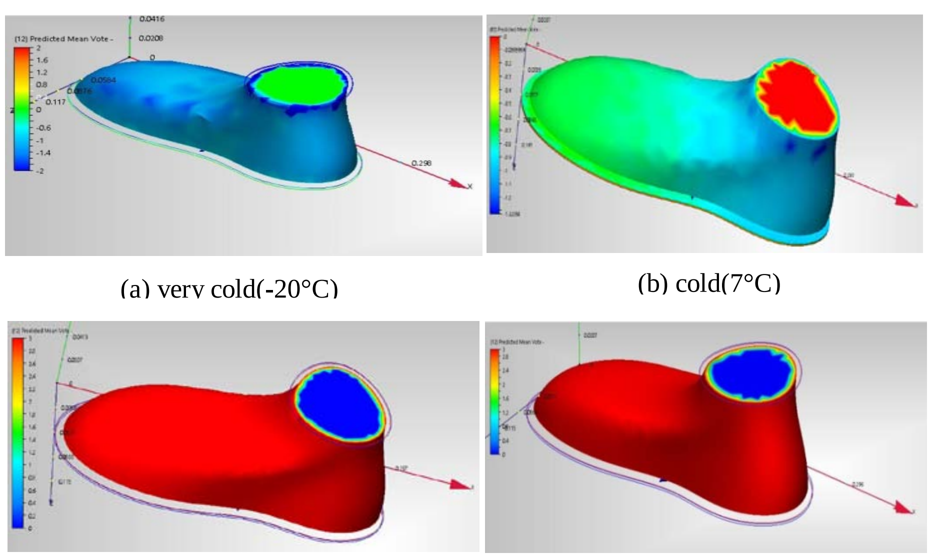


(a) At toe portion (b) At heel portion (c) At bottom portion

Figure 7: Thetemperature profile in case of very hot (50°C)weather

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 shoe.

According to PMV in figure 8., the occupant (human foot) felt, neutral to slightly cool in the cold weather and felt slightly warmtovery hot in the hot weather within the shoe according to ASHRAE thermal sensation scale(ANSI/ASHRAE Standard 55, 2004)(Table 4) and their PPD is up to 25%, 24%,99.1% and 99.1% respectively shown in figure 9. The level of satisfaction comparatively increased in very cold condition (25%) due to the closed air-tight opening of the shoe.



(a) very cold(-20°C) (b) cold(7°C)

(c) hot(40°C) (d) very hot(50°C)

Figure 8: Comparison of PMV among four different weather conditions

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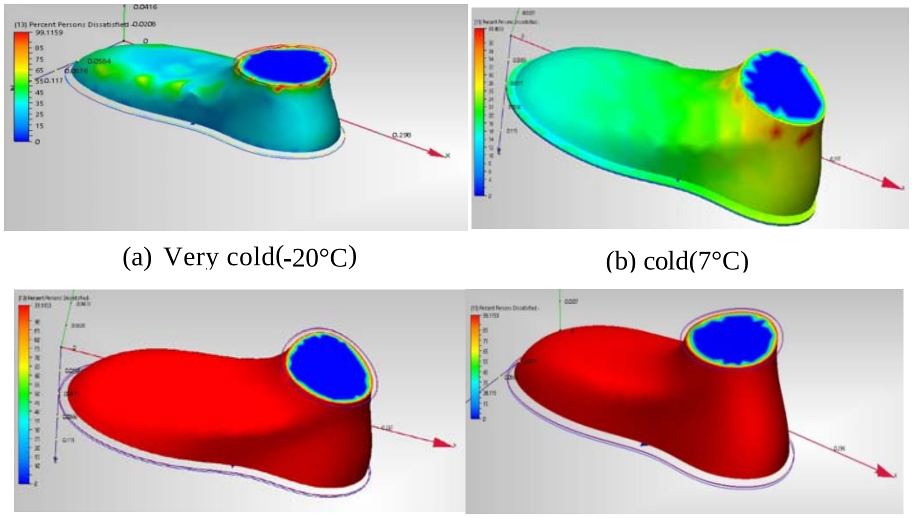

(a) Very cold(-20°C)

(b) cold(7°C)

(c) hot(40°C)

(d) very hot(50°C)

Figure 9: Comparison of PPD among four different weather conditions

The result says that the footwear is near the comfort range only in cold regions with closed air-tight at the opening of the shoe.

Table 4: ASHRAE Thermal sensation scale

Value	Sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

VI. Conclusions

A simple 3D model has been developed successfully to simulate in-shoe temperatures in various locations using CFD simulation. These models covered different temperature as boundary conditions. Predicted temperature distributions in the foot and shoe indicate greater heat transfer in the toe region in case of hot weather, but in the cold weather temperatures were increased and distributed evenly. This model demonstrated an approach to simulating in-shoe microclimatic conditions, with promising results. The modeling results were then linked to the thermal comfort index to assist shoe manufacturers to design footwear with better thermal comfort properties. Occupant's (human foot) PMV and PPD values were not acceptable according to ASHRAE thermal sensation scale when used in hot weather condition due to felt hot in this region. Because of the very high temperature around the human foot experienced approximately 99.1% discomfort in this situation. On the other hand, PMV and PPD values were quite acceptable when the footwear was used in cold weather condition hence the human foot felt neutral to slightly cool in this situation according to ASHRAE thermal sensation scale. Here the human foot experienced only 25% discomfort which showed a good option according to the foot comfort range. Now it can be concluded that the designed footwear model is comparatively best for use in cold weather. 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.

Acknowledgement

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