University of Nevada, Reno

Assessing Thermal Comfort in Deep Underground Mines

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mining Engineering

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ABSTRACT

The importance of workers maintaining relative body comfort in deep hot underground mines is of great significance. This is because productivity, health, safety and the bottom line of mine operations depend on it. Comfort studies have been extensively researched, especially in the built and meteorological fields resulting in an avalanche of recommendations for their evaluation. Nevertheless, no known or accepted mode for comprehensively assessing the thermal condition of the mining environment is currently available. Current literature presents several methods and techniques but none of these can expansively assess the underground mine environment since most methods consider only one or a few defined factors and neglect others. Some are specifically formulated for the built and meteorological climates thus, making them unsuitable for underground mine situations. This thesis presents an approach in the form of a comfort model which will apply comfort parameters in assessing extensively the climate conditions of the deep, hot, and humid underground mines. This method considers both human and climate parameters in the human comfort equation and hence offers a more inclusive assessment. Simulation analysis predicted comfort limits in the form of required sweat rate and maximum skin wettedness. Tolerable worker exposure times to minimize thermal strain due to dehydration are predicted. Optimal ambient air temperatures, humidities and activity rates of miners for comfort are also predicted. The analysis determined the optimal air velocity for thermal comfort to be 1.5 m/s. The results also detected humidity to contribute more to deviations from thermal comfort compared to other comfort parameters. It is expected that this new approach will significantly help in managing heat stress issues in underground mines and thus improve productivity, safety, and health.
DEDICATION

This thesis is dedicated to my parents, who gave me the greatest support throughout my life and education.

Also, to the rest of my family, brothers and sisters with my sincere love and especially to you: Marilynn Nwintiema Sunkpal.
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CHAPTER 1: INTRODUCTION

1.1 Motivation

In contrast to other industries such as the built environments, in terms of the quantification of key parameters affecting human comfort, underground mine operators have seemingly paid more consideration to traumatic injury, dust, noise, gas exposures, infra-red exposures in their operating processes, but less attention to the thermal comfort of mine workers.

Hot and humid climates are encountered in deep underground mines, where the virgin rock and air temperatures increase with depth due primarily to the geothermal gradient, increasing air pressure from auto-compression of the air column downcasting vertical openings (e.g. ventilations shafts), and groundwater. Mine water transfers heat and vapor to the ventilating air by evaporation and the air collects the heat liberated by mining machinery and equipment as well as less important sources of heat comprising oxidation activities, human metabolism, explosive blasting, rock movement, and pipelines.

Thermal comfort is defined as the absence of discomfort in the workers’ environment, implying the condition when someone is not feeling either too hot or too cold. A number of factors have a substantial impact on the thermal comfort of an occupant's environment and thus can be divided into personal and environmental factors. Personal factors include clothing, personal activity and condition. Environmental factors comprise thermal radiation, temperature, air velocity and humidity.
As soon as people are discontented with their thermal environment, not only is it a likely safety and health hazard, it also impacts on their ability to function proficiently, their satisfaction at work, the likelihood they will produce greater results culminating in increase productivity, attainment of the company’s goals and a lot more.

The “human thermal environment” is extremely unpredictable and cannot be conveyed in temperature units of degrees. It cannot also be adequately defined by an acceptable temperature ranges. Due to individual differences, it is not possible to specify a thermal environment, which will gratify everyone. For example, a person walking upstairs in a cold environment whilst wearing a coat may feel too hot, whilst someone sitting still in a shirt in the same environment may feel too cold.

Skin is one of the most important organs for thermoregulation function of the human body. It has distributed over its surface, a great number of cold/warm receptors connected to the hypothalamus that respond to changes of ambient temperature and promote the maintenance of constant body temperature through dilating or constricting blood vessels in the skin appropriately (ASHRAE, 2005). Since skin temperature is responsible for the initiation of behavioral thermoregulation, it is of great importance in humans to maintain body temperature homeostasis (Weiss, B; Laties, V, 1961). Most indices currently being used are silent on this important parameter.

According to Fanger (Fanger, 70), an environment can be said to achieve reasonable comfort when “at least 80% of its occupants are thermally comfortable”. This means that thermal comfort can be assessed simply by surveying subjects to find out
whether they are dissatisfied with their environment. This, however, will generate problems since such survey will not be ideal for planning for comfort for all occupants.

According to Ye et al. (2007), current thermal comfort studies are based on the PMV (Predicted Mean Vote) model developed by Fanger. However, the PMV model mainly presents the relationship between thermal perception and the environmental parameters and does not make clear the physiological and subjective respond of people to heat and the thermal environment (Ye, et al., 2007).

Comfort assessment indices for the human body’s thermal conditions in hot and humid climates comprise; but are not limited to dry and wet-bulb temperatures (Hardlane, 1905), Effective Temperature (ET) (ASHRAE, 2005), Wet-bulb Globe Temperature (WBGT) (ISO 7243, 1989), Heat Stress Index (HSI), work and recovery heart rate, body temperature (NIOSH, 1986). Despite their heavy dependence for comfort analysis, some of these indices have not been reviewed for a long period of time and are mostly based on subjective methods. For example, ISO 7243 (1989) recommends a wet-bulb temperature threshold limit value (TLV) of 32°C but this is only based on responses of workers recorded over the past years. Equally, none of the above parameters can comprehensively assess the thermal status of miners for comfort. For example, dry or wet-bulb temperatures, ET, WBGT, and HSI incline to focus on the environmental conditions without allowing for a worker’s actual thermal status, as the heart rhythm or body temperature only shows the conditions of a human body without explicitly considering the complex interaction of human skin or respiration with the environment (Epstein & Moran, 2006).
1.2 Research Objectives

This work will apply a mathematical model for assessing and predicting the comfort conditions in underground mines. The mean skin temperature will be predicted based on the comfort parameters; and using empirical data typical of an operating underground mine in western USA, in conjunction with applying the powerful effect of thermodynamic heat exchange between the body and its environment, comfort limits in the form of required sweat rate, maximum allowable exposure time and the maximum skin wettedness will be predicted to help in planning and designing for comfort in underground mines.

A critical analysis of the human body’s heat balance will also be made. Human metabolic processes are associated with heat production in accordance with the laws of thermodynamics. From the metabolic point of view, the generation of heat is a secondary effect, but when one is concerned with the thermoregulation of body temperature, metabolic heat is of fundamental interest. The human body temperature is maintained at a constant balance much greater than that of the surroundings, as a result of a high rate of heat production governed by regulatory mechanisms.

The work presented in this thesis is a part of the NIOSH-sponsored research project titled: “Assessing, Modeling, and Cooling Mine Underground Workings in Deep and Hot Mines” at the University of Nevada, Reno. The team includes Mr. Pedram Roghanchi, Miss Kareenna Carpenter, Mr. Chao Lu and Mr. William Asante under the supervision of Dr. Kocsis (Principal Investigator) and Dr. Danko (Co-PI).
1.3 Thesis Organization

This thesis is structured in the following order in dealing with this problem.

Chapter 2: Heat Sources in Underground Mines

In this chapter, a literature review of heat sources in underground mines is discussed. A prolonged exposure of people to unfavorable thermal conditions inevitably leads to an increase in body temperature, which can consequently generate heat illnesses and physiological effects that can significantly affect their work efficiency.

Chapter 3: Miner Thermal Comfort

This chapter gives an analysis of human comfort as a result of unfavorable climatic conditions in underground mines. Human thermal comfort is a combination of a subjective sensation and several objective interactions with the underground environment.

Chapter 4: Skin Temperature and Comfort, a Review

The skin temperature is an important physiological parameter for the assessment of thermal comfort in a working man. This chapter is intended to explain those characteristics of human thermal composition, heat and moisture content transfer from the skin surface, and human thermal comfort, that could be useful for designing and selecting clothing for mine workers and other types of skin covering.

The body regulates temperature like the radiator of a machine. It is constantly producing heat and then dispersing it through various processes. Heat loss can be accomplished through the processes of conduction, convection, radiation, and evaporation. In all these process, the skin serves as the mediator between the body and its environment.
Chapter 5: Mathematical Model Application Process

This chapter presents the methodology for developing the model. Thermal comfort, as in many facets of environmental control, is much easier to define than achieve. It is not a simple matter of regulating the temperature of the mine environment to please all mine workers.

The fact that ASHRAE describes thermal comfort as achieved when climatic conditions please eighty percent (80%) of occupants gives a glimpse of just how difficult it is to please all occupants even some of the time. The most regular occupant complaint is either it is too cold or too hot. These conditions are not simply a function of ambient temperature, but of radiant temperature, air velocity, relative humidity, and air temperature whose values may vary from climate to climate.

The ISO 7933 2004 standard (ISO 7933, 2004) entitled “Hot environments—Analytical determination and interpretation of thermal stress using calculation of the predicted heat strain”, proposes limit values allowing to predict the physiological evaluation of a person when exposed to an environment described by six primary parameters of air temperature and humidity, radiation, air velocity, metabolic rate and clothing insulation.

This study used the principles in this standard to provide mine operators with a set of comparable methods well-defined and simple to use and is expected to enable them to protect mine workers more efficiently, more promptly and more economically.

Chapter 6: Miner Thermal Comfort Analysis
In this chapter, the results of the simulation and comfort analysis are presented and application of these results in managing thermal stress in mines is discussed.

**Chapter 7: Conclusions**

In this chapter, the benefits of the research study in the mining industry are presented along with recommendations for future work.
CHAPTER 2: HEAT SOURCES IN UNDERGROUND MINES, A REVIEW

In this chapter, a literature review of all major heat sources in underground mines is discussed. A continued exposure of underground mine workers to unfavorable thermal conditions certainly leads to an increase in body temperature and consequently produces physiological effects that affect their work efficiency.

2.1 The Mining Thermal Environment

Human thermal environments is a division of Ergonomics Science. It is concerned with the thermal comfort (i.e. a persons’ sensation to cold or heat) of human beings in any, but exclusively in their occupied environment. Convection, conduction, radiation and protective or insulating properties of the human body and the environment in which it is located are all factors whose effects are closely considered in this science. The aim of this science is to control these factors in the environment and/or the insulating or clothing properties of the individual to achieve 'thermal comfort'; the state in which a subject is satisfied with their perceived thermal state. This has prompted the need to produce an adequate climate within the working areas, to maintain the health and safety of the workforce.

Minerals extraction at greater depths, engaging high-powered machinery to increase production levels has forced a bigger burden on mine ventilation systems to maintain an acceptable and safe working environment. A worsening in the climate conditions experienced in these workings may also unfavorably affect the health and safety of the workforce. Underground mines are now being operated at considerable depths of
over 2,000-3,000 m (6,500-9,800 ft.). In addition, the heavy presence of machinery has permitted improved production and development rates to be achieved at the cost of increased emissions of dust, gas, heat and humidity (Lowndes, Crossley, & Yang, 2004).

The main objective of mine ventilation is to provide comfort to the occupants and machinery by supplying enough quality air to dilute and remove obnoxious gasses from the occupied workings. In similar fashion, the main objective of the study of thermal comfort conditions is generally to be able to determine the conditions for accomplishing human internal thermal neutrality. To do this, there arises the need to study the human body's response to certain environmental conditions (ISO 7730, 2005).

### 2.2 Heat Sources in Underground Mines

Metabolism in humans is accompanied by heat generation, with the core body temperature remaining a constant at about 36.9°C (37 ± 1°C) and in contact with surrounding climate temperature; mine workers have sensations expressed as either warm or cold. When workers are subjected to ambient temperatures greater than the threshold limits, it causes physiological effects expressed in the following forms: loss of attentiveness to other people’s activities, taking regular rests or breaks, a longing to hurriedly complete the task, irritability, reduced concentration and reduction in sensitivity (Navarro Torres & Raghu, 2011).

The condition may worsen if the temperature of the air surges beyond tolerable limits. The status quo becomes more precarious especially when the humidity of air also increases concurrently. A prolonged exposure of people to unfavorable thermal conditions inevitably leads to increase in body temperature, which consequently produces
physiological effects that affect their work efficiency, and a series of disorders known together as heat illnesses. Figure 2.1 shows a relationship between work efficiency and effective temperature or wet bulb temperature and air velocity. It is worthy of note that a prolonged exposure of a worker to temperatures exceeding 42°C (107.6°F) may cause irreversible damage to the critical organs or even death.

![Figure 2.1: Effect of temperature on work efficiency (Ramani, 1992)](image)

In underground mines, there are many sources of heat which cause the increase of temperature of air during its travel through mine airways. The mines intake air temperature gradually increases due to the depth and the length of air travel through the underground opening. One of the main sources of heat in underground mines is the strata temperature. The increase of strata temperature as a function of depth is known as the “geothermal gradient”. Other sources of heat to the air in the underground atmosphere are air auto-
compression, machinery emission, explosive detonation, human metabolism and mine water thermal influx.

Typical heat generating sources underground are discussed in brief:

### 2.3 Surface Air Temperature

The temperature of the surface air can have a significant impact on the air temperature underground. The surface air temperature can influence the temperature of air flow in the atmosphere of underground openings during particular seasons of the year and depends on the altitude of the mine.

Work done by Navarro Torres & Raghu (2011) indicates that during winter times or in mines located at high altitudes, such as the South America Andes, the outside temperature has little or no influence on the temperature of underground openings.

Average dry bulb temperature measured in mine stopes located at a depth between 750 m to 770 m in mines located in the North Hemisphere, compared with a variation of external dry bulb temperature, observed clearly the effect of surface air temperature in underground openings (see Figure 2.2). Therefore, the maximum temperature on the hottest month will be critical (Navarro Torres & Raghu, 2011). They contend that, as a part of an environmental thermal comfort evaluation in deep, hot and humid underground mines, it is necessary to consider the surface temperature, for the reason that this is the initial temperature, $t_1$ of the intake air to underground openings. For similar conditions at mine depths of 750 m, variation in underground openings temperature, $\Delta t_s$, can be calculate by equation (2.1), based on surface air temperature, $t_a$. (Navarro Torres & Raghu, 2011).
\[ \Delta t_e = 0.301t_a - 2.107 \] (2.1)

Also, a study done by Sibisi (2014) to ascertain the effect of surface temperature on refrigeration plant design is worth taking note of. Owing to the difference in input surface temperatures at the two mines, Mine A’s refrigeration requirement was about 4 MW more than mine B. This proves that a lower surface temperature will have less impact on the air temperature underground compared to higher surface air temperatures.

Figure 2.2: Variations in underground openings air temperature, due to surface air temperature differences, [Navarro Torres & Raghu, 2011]

2.4 Auto-Compression Heat Generation

Surface air sent down to the underground workings, through either natural or man-made ventilation, will experience a compression. This means that although the volume of air has been reduced, the amount of heat remains the same resulting in hotter air.
In strict terms, auto-compression is not a source of heat, for it results in an increase in temperature of either air or water as a result of the conversion of potential energy into enthalpy, and not as a result of a flow of heat from an external source (Wagner, 1987). The term auto-compression should in a strict sense only be applied to compressible fluids, of which ventilation air is an example. The change in enthalpy $H$ as a result of auto-compression is (Wagner, 1987):

\[(H_2 - H_1) = g \times (Z_1 - Z_2)\]  

(2.2)

$H$ is enthalpy of fluid [J/kg], $Z$ is elevation above a certain datum level [m] and $g$ is gravitational acceleration, $g = 9.81 \text{ m/s}^2$. The change in temperature, $\Delta t$ corresponding to the change in potential energy is (Wagner, 1987):

\[\Delta t = t_2 - t_1 = \frac{g \times (Z_1 - Z_2)}{C_p}\]  

(2.3)

The numerical values of $C_p$ for air is 1,014 J/kg°C.

For example, a change in elevation of 1,000 m, the corresponding increase in air temperature is 9.66 °C (Wagner, 1987). In the case of ventilating air, changes in moisture content and its effect on the thermal capacity of the air have to be considered as well. In deep mines, the increase in the temperature of ventilating air (auto-compression) is significant and a major factor contributing to climatic difficulties. Since the effect of auto-compression combines with the surface air temperature to contribute to underground air temperature, it is clear that this is a very significant source of mine heat, particularly in hot areas of the world (Wagner, 1987).
2.5 Heat Generation due to Thermal Properties of Rock Mass

The temperature of the undisturbed rock (virgin rock temperature) increases with depth below the surface. The change in temperature is the result of the flow of heat from the interior of the earth, which is reasonably constant at about 0.05 W/m² (Hemp, 1989; Voß, 1981), although considerable variations do occur. The actual virgin rock temperature (VRT), will depend upon the thermal properties of the rock, the rock temperature close to the surface, where it is reasonably constant and is not influenced by surface temperature changes, and the temperature gradient, Δt. (Hemp, 1989; Voß, 1981):

$$VRT = t_s + Δt \cdot (D - d_s)$$  

VRT = virgin rock temperature at depth D [°C]

$$t_s =$$ rock temperature at depth d_s [°C]

$$Δt =$$ temperature gradient [°C/m]

$$D =$$ depth below surface [m]

$$d_s =$$ depth below the surface where t_s is measured [m]

Table 2.1 provides an overview of the geothermal environment for major mining districts. The table shows that the increase of virgin rock temperature for every 100 m of the depth ranges from about 1 to nearly 10 °C. Apart from regional differences, there can be local variations of virgin rock temperature as well (Hemp, 1989; Voß, 1981).
Conduction is part of the processes by which heat is transferred from the virgin rock to the mine workings. Two processes are involved: the conduction of heat through the surrounding rock mass towards the mine excavation, and the transfer of this heat from the excavation walls to the air or water flowing through the excavation, which is a convective process. This process is strongly dependent on surface conditions and the nature of the mine atmosphere.

Table 2.1: Virgin rock temperatures in different mining districts [Hemp, 1989; Voß, 1981].

<table>
<thead>
<tr>
<th>District</th>
<th>Country</th>
<th>Depth range [m]</th>
<th>Temperature gradient [°C/m]</th>
<th>Depth gradient [m/°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Witwatersrand</td>
<td>South</td>
<td>100 – 3,800</td>
<td>0.009</td>
<td>117</td>
</tr>
<tr>
<td>Klerksdorp (gold)</td>
<td>South</td>
<td>1,000 – 2,500</td>
<td>0.011</td>
<td>95</td>
</tr>
<tr>
<td>Bushveld igneous</td>
<td>South</td>
<td>200 – 2,500</td>
<td>0.021</td>
<td>48</td>
</tr>
<tr>
<td>Kolar (gold)</td>
<td>India</td>
<td>400 – 3,000</td>
<td>0.014</td>
<td>74</td>
</tr>
<tr>
<td>Moro Velo (gold)</td>
<td>Brasil</td>
<td>1,000 – 2,500</td>
<td>0.010</td>
<td>100</td>
</tr>
<tr>
<td>Copper district</td>
<td>Zambia</td>
<td>400 – 1,200</td>
<td>0.015</td>
<td>68</td>
</tr>
<tr>
<td>Butte (copper)</td>
<td>USA</td>
<td>1,200 – 1,400</td>
<td>0.090</td>
<td>11</td>
</tr>
<tr>
<td>Sudbury (nickel)</td>
<td>Canada</td>
<td>700 – 1,700</td>
<td>0.009</td>
<td>117</td>
</tr>
<tr>
<td>Coal</td>
<td>Hungary</td>
<td>50 – 600</td>
<td>0.046</td>
<td>22</td>
</tr>
<tr>
<td>Ruhr district (coal)</td>
<td>Germany</td>
<td>300 – 1,500</td>
<td>0.039</td>
<td>26</td>
</tr>
</tbody>
</table>

2.6 Heat generated by Machinery

The equipment that generate and transfer heat to the ventilation current in underground atmosphere are as follows:

- Mobile diesel and electrical equipment, such as jumbo drills, trucks, LHDs, pumps, locomotives, etc.
• Electrical and non-mobile equipment (fans, lighting, pumps, hoists, stations or transformer substations, etc.).

Diesel equipment contributes significantly to the overall heat load of the airflow in the underground atmosphere. Diesel engines fuel consumption for mining equipment is 0.24 kg/kWh, with a calorific value of 44 MJ/kg (Vutukuri & Lama, 1986), so the total energy released is $0.24 \times 44 \times 103 \text{ KJ/kWh} = 10560 \text{ KJ/kWh} = 176 \text{ KJ/min} = 2.9 \text{ KJ/s kW} = 2.9 \text{ kW/kW}$. Of the total 2.9 kW energy release, 34% (1 kW) is converted into mechanical energy and 66% (1.9 kW) is transferred to the ventilating air. It is important to note that this energy is not totally transferred to the airflow because it depends on the effective time for which the equipment is used, so it is different for each condition of underground work and the value is around 0.9 kW (31%).

Diesel equipment heat exhaust $q_{ed}$ (KW) can be expressed by equation (2.5) as follows (Vidal and Singh, 2011):

$$q_{ed} = f_m \cdot f_t \cdot q_d \cdot P_d$$

Where;

$q_{ed}$ is the equivalent energy released by the diesel fuel ($\frac{2.9 \text{ kW}}{\text{kW}}$)

$P_d$ is the equipment engine (kW)

$f_m$ is mechanical efficiency and $f_t$ is equipment utilization efficiency. Based on equation (2.5), the temperature variation of air due to exhaust from the diesel equipment $\Delta_{td}$ (°C) can be quantified by the following equation:
\[ \Delta t_d = \frac{f_m f_t q_d p_d}{\rho_a C_e Q} \]  

(2.6)

### 2.7 Heat Generated from Explosive Blasting

Fairly large amounts of heat are liberated when explosives are used. The heat is transferred to the rock, most probably to the broken rock and released over fairly long periods of time. The heat liberated by explosives depends on the type of explosive and varies from about 4,500 to 3,800 kJ/kg. The heat \( q_e \) (kW) released by explosives during blasting is calculated using equation (2.7) (Navarro Torres & Raghu, 2011):

\[ q_e = \frac{E_e q_e}{86400} \]  

(2.7)

The thermal influence due to blasting \( \Delta t_e \) (°C) can be quantified by equation (2.8) as follows:

\[ \Delta t_e = \frac{E_e q_e}{86400 \cdot \rho_a C_e Q} \]  

(2.8)

Similar to diesel exhaust heat, the heat due to explosive detonations influences the local atmosphere only.

### 2.8 Heat due to Human Metabolism

The heat generated by human metabolism is not significant and can be ignored (Hartman, Mutmansky, Ramani, & Wang, 1997), typical figures are:

- At rest 90 to 115 W
- Light work rate 200W
- Moderate work rate 275 W
• Hard work rate 470 W

Thus, when the number of people or workers in an underground environment is large, temperature increase by human metabolism $\Delta t_h$ ($^\circ$C) can be expressed by equation (2.9), where $qh$ is the human heat release and it is a function of effective temperature (kW/person) and, $n$ is the total number of humans involved (Hartman, Mutmansky, Ramani, & Wang, 1997).

$$\Delta t_h = \frac{q_h n}{\rho_a C_e Q} \quad (2.9)$$

### 2.9 Heat from Underground Water

Two sources of water are encountered in mining: Groundwater or Mine water. All groundwater, especially from hot fissures and natural rock reservoirs, is a prolific source of heat in mine workings. Since water and heat are both derived from the surrounding rock or geothermal sources, the water temperature will approach or even exceed the rock temperature. The water transfers its heat to the mine air, mainly by evaporation increasing the latent heat of the air. The total heat gain from hot underground water in open channel flow $q_w$ (kW) can be calculated from the equation (2.10) (Navarro Torres & Raghu, 2011):

$$q_w = F_{tw} C_w (t_{tw} - t_a) \quad (2.10)$$

Where:

$F_{tw}$ is weight flow rate of thermal water (kg/s)

$C_w$ is specific heat of water (4.187 kJ/kg$^\circ$C), and
$t_w$ and $t_a$ are water temperatures at points of emission and exit from the mine airway in ($^\circ$C), respectively.

The thermal influence of underground ventilation air flow can be calculated by equation (2.11) as follows (Navarro Torres & Raghu, 2011):

$$\Delta t_w = 4.187 \cdot \frac{F_{tw}C_w(t_{tw} - t_a)}{\rho_aC_eQ}$$  \hspace{1cm} (2.11)

### 2.10 Other Sources of Heat

Oxidation of carbonaceous matter and some sulfide ores can increase the heat load in mines and in extreme cases can lead to spontaneous combustion.

Cemented backfill offers many advantages in terms of strata control in deep mines. One of the drawbacks of this type of fill is the heat of hydration, which can have very adverse effects on the climatic conditions in a mine.

### 2.11 Summary

The total variation of temperature in an underground environment $\Delta t$ total can be calculated by including the variation of temperature from air auto-compression $\Delta t_a$, thermal properties of rock $\Delta t_r$, heat emission from diesel equipment $\Delta t_d$, heat due to ore/rock breaking processes through the use of explosives $\Delta t_e$, human metabolism $\Delta t_h$ and thermal water $\Delta t_w$ as outlined in equation (2.12):

$$\Delta t_{\text{total}} = \Delta t_a + \Delta t_r + \Delta t_d + \Delta t_e + \Delta t_h + \Delta t_w$$  \hspace{1cm} (2.12)

With increasing mining depths, the impact of thermal properties of the surrounding rock mass becomes more important (Navarro et al, 2008). Based on equation (2.12), the
total underground atmosphere temperature $T_2$, will be expressed by equation (2.13), which is a function of surface temperature $t_s$ and underground opening primary temperature $T_1$:

$$T_2 = t_s + \Delta t_{\text{total}} \quad \text{or} \quad T_2 = T_1 + \Delta t_{\text{total}}$$  \hspace{1cm} (2.13)
CHAPTER 3: MINER THERMAL COMFORT

Convective, conductive, radiative and insulating properties of the human body and the climate in which it is located are all variables whose effects are closely considered in the comfort science. In achieving comfort, the aim is to manipulate these variables in the environment and/or the clothing of the individual until the state in which the individual is content with their perceived thermal state.

This chapter highlights the overview of human thermal environment parameters that effect on human comfort, the heat balance equation for the human body, mathematical models to predict thermal comfort and the most widely used thermal comfort indices.

3.1 Underground Mine Thermal Comfort and its Controlling Parameters

Providing a satisfactory thermal environment for mine workers is rather complex, because of the subjective nature of the human response and the multitude of interacting variables. There are six main factors affecting the mine thermal comfort, which can be perceived as both environmental and personal. The environmental factors comprise four parameters that affect the environment around the human body and, therefore, its capacity to facilitate transfer heat. These parameters are principally;

i) **The Air Temperature** termed as $Ta$ and is defined as the temperature of the ambient air surrounding the occupant that defines the net heat flow between the human body and its environment. Temperature is the most significant component to the experience of comfort in an environment. Our bodies perform within an internal temperature range considerably narrower than external
temperatures. In the process, our bodies’ metabolism generates heat, which must dissipate into the surrounding air or surfaces. When surrounding temperatures are high, this process becomes more difficult and we may overheat or feel warm. When surrounding temperatures are low, the rate of heat loss becomes more rapid, and we may feel uncomfortably cold (Boduch and Fincher, 2010).

ii) **Mean Radiant Temperature** $Tr$ arises from the fact that the net transfer of radiant energy between two objects is just about relative to their temperature difference multiplied by their capacity to radiate and absorb heat also known as their emissivity. Also, the $Tr$ can be defined as the temperature of a uniform enclosure “with which a small black sphere at the test point” would have the same radiation transfer as it does with the real environment (Boduch and Fincher, 2010). The use of the sphere in the definition is to show the average in three dimensions. $Tr$ also has the strongest influence on the thermophysiological comfort indices.

iii) **Relative Air Velocity** defines the movement of air across the layer of skin or clothing surface area, thus convecting heat. Design air velocities inside mines working faces tend to range from 0.3 and 4.0 m/s (McPherson, 1984; Mousset-Jones, 1986). Air velocity plays a role in the perception of thermal comfort. In hot climate, as the body attempts to cool itself, the flow of air across the body will assist in evaporative cooling as a consequence of sweating. When the humidity of air is near saturation (i.e. near 100 % relative humidity), the air next to the sweating body may become saturated with moisture, but by moving the
air next to the body away and bringing in fresh, lower humidity air, the evaporation of sweat can continue. Mechanisms of convection can further move the heat generated by metabolic processes from the skin and into the surrounding air. All this leads to continued cooling, and the higher the velocity of air, the more effective is the process.

iv) **Humidity** is defined as the amount of water vapor in a given space; while the humidity ratio or specific humidity is defined as the weight of water vapor per unit weight of dry air. Relative humidity (RH) is the ratio between the actual amount of water vapor in the air and the maximum amount of water vapor that the air can hold at that air temperature. While temperature is the most important factor in generating a phenomenological sense of thermal comfort, relative humidity plays a large part in conjunction with temperature to provide a sense of discomfort. High levels of relative humidity can work against the evaporative cooling effects of sweating and leave the body prone to over-heating. Human beings are sensitive to slight temperature changes, yet cannot perceive differences in relative humidity levels within the range of 25% and 60%, which is the primary reason that this range is often cited as the baseline (Lstiburek, 2003). If relative humidity falls outside this range, there are notable effects. When relative humidity gets too high, discomfort develops, either due to the feeling of the moisture itself (ASHRAE, 2005) which is unable to evaporate from the skin, or due to increased friction between skin and clothing with skin moisture (ASHRAE, 2005). When relative humidity gets too low, skin and mucous surfaces become drier, leading to complaints about dry nose, throat,
eyes, and skin (Lstiburek, 2003). Air in mine working faces is nearly saturated, with relative humidity commonly ranging from 90% to 100%. Water vapor fraction pressure can be calculated from relative humidity.

The personal or human factors are two, which depend on the nature of the miners’ state or level of activity:

**Clothing Thermal Resistance:** which describes the thermal resistance or insulation level between the human body and its environment, with the clothing insulation typically quantified in terms of its Clo values (1 Clo = 0.155 m²/W insulation value). Table 3.1 presents an estimation of some types of clothing insulation used by miners.

**The Activity Level,** that is the work or metabolic rate that controls the generated heat inside the human body as we carry out physical activity. Hence, the metabolic rate depends on the activity level and the fitness level. The estimate of metabolic rate for various activity levels is depicted in Table 3.2 (ISO 7243, 1989).

Although the personal and the environmental factors might be independent, together they contribute to the thermal comfort state; as one of these variables changes, others need to be adjusted to maintain the thermal equilibrium. This is depicted in Figure 3.1.

**Table 3.1: Clo Parameters Used by Miners (Waclawik & Branny, 2004)**

<table>
<thead>
<tr>
<th>Type of Clothing</th>
<th>Rcl, clo, (m²)/W</th>
<th>fcl</th>
<th>hcl=1/R, W/(m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naked</td>
<td>0.000</td>
<td>1</td>
<td>∞</td>
</tr>
<tr>
<td>Shorts</td>
<td>0.051</td>
<td>1.05</td>
<td>19.6</td>
</tr>
<tr>
<td>Shorts and a thin short sleeved shirt</td>
<td>0.078</td>
<td>1.11</td>
<td>13.2</td>
</tr>
<tr>
<td>Thin trousers, short-sleeved shirt</td>
<td>0.093</td>
<td>1.18</td>
<td>10.8</td>
</tr>
<tr>
<td>Thick trousers, long sleeved shirt</td>
<td>0.116</td>
<td>1.28</td>
<td>8.6</td>
</tr>
<tr>
<td>Overalls, long shirt</td>
<td>0.155</td>
<td>1.28</td>
<td>6.5</td>
</tr>
</tbody>
</table>
Table 3.2: Estimate of metabolic rate for activity (ISO 7243, 1989)

<table>
<thead>
<tr>
<th>Rating</th>
<th>Activity</th>
<th>Metabolic Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Resting</td>
<td>$M \leq 117$ W</td>
</tr>
<tr>
<td>1</td>
<td>Low metabolic rate</td>
<td>$117 &lt; M \leq 234$ W</td>
</tr>
<tr>
<td>2</td>
<td>Moderate metabolic rate</td>
<td>$234 &lt; M \leq 360$ W</td>
</tr>
<tr>
<td>3</td>
<td>High metabolic rate</td>
<td>$360 &lt; M \leq 468$ W</td>
</tr>
<tr>
<td>4</td>
<td>Very high metabolic rate</td>
<td>$M &gt; 468$ W</td>
</tr>
</tbody>
</table>

Figure 3.1: Personal and the environmental factors interact together to contribute to the thermal comfort state

3.2 Heat Balance Equation for Human Body

The sum of the heat gains and losses by the human body is expressed by the heat balance equation. By applying the first law of thermodynamics to the human body, it is
possible to assess its thermal balance by means of the following well-known equation (Fanger, 1970):

$$S = M - W - (C_{res} + E_{res} \pm (C + R) + E)$$  \hspace{1cm} (3.1)

Where, M is the metabolic rate of the body that provides energy, W is the rate of mechanical works, E is the rate of heat loss through evaporation, R is the radiation rate, C is the convection, and S is the body heat storage rate, all have the same unit of Wm$^{-2}$.

The terms in this equation can be logically expressed as a function of the Climate and physiologic parameters (Table 3.3 and Table 3.4). In the heat balance equation S is the storage flow of sensible heat in the body tissue, which means body heating when positive and cooling when negative. When $S$ is equal to zero the amount of heat that is produced in the body and gained from the environment is the same as that lost to the environment, and the body temperatures are in a steady state.

**Table 3.3: Comfort Parameters in the Thermal Balance Equation [Fanger, 1970].**

<table>
<thead>
<tr>
<th>Terms in the thermal balance equation</th>
<th>Comfort Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
</tr>
<tr>
<td>Metabolic power, M</td>
<td>●</td>
</tr>
<tr>
<td>Mechanical power, W</td>
<td>●</td>
</tr>
<tr>
<td>Respiratory convective heat loss, C$_{res}$</td>
<td>●</td>
</tr>
<tr>
<td>Respiratory evaporative heat loss, E$_{res}$</td>
<td>●</td>
</tr>
<tr>
<td>Convective heat loss, C</td>
<td>●</td>
</tr>
<tr>
<td>Radiation heat loss, R</td>
<td>●</td>
</tr>
</tbody>
</table>
**Table 3.4: Factors Influencing the Heat Balance Equation [Blankenbaker, 1982]**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Environment</th>
<th>Human</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metabolism (M)</td>
<td>Little effect</td>
<td>Activity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Weight</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Surface area</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Age</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sex</td>
</tr>
<tr>
<td>Evaporation (E)</td>
<td>Wet-bulb temperature</td>
<td>Ability to produce sweat</td>
</tr>
<tr>
<td></td>
<td>Dry-bulb temperature</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Velocity</td>
<td></td>
</tr>
<tr>
<td>Radiation (R)</td>
<td>Temperature difference between bodies</td>
<td>Surface area</td>
</tr>
<tr>
<td></td>
<td>Emissivity of surfaces</td>
<td></td>
</tr>
<tr>
<td>Convection (C)</td>
<td>Dry-bulb temperature</td>
<td>Clothing</td>
</tr>
<tr>
<td></td>
<td>Velocity</td>
<td>Mean body surface temperature</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Surface area</td>
</tr>
</tbody>
</table>

The terms of this equation can be logically expressed as a function of the Climate and physiologic parameters. Consequently, Fanger’s, comfort equation can be written in the form:

\[
f(M, I_{cl}, V, T_a, T_{rm}, H, \text{clo}) = 0\]  

(3.2)

Where;  
M = metabolic rate, met, I_{cl} = cloth index, clo, V = air velocity, m/s, T_{rm} = mean radiant temperature, ³C, T_a = ambient air temperature, ³C, H = Humidity, Pa.

Discussing each term briefly can highlight its contribution and impact:

**The Metabolic Rate** is the energy released per unit time by the oxidation processes in the human body and is dependent on the amount of muscular activity. Metabolic rate varies according to the activity performed. It is often measured in met [1 met = 50 kcal/h/m²] and is proportional to the body weight, activity level, body surface
area, health, sex, age, amount of clothing, surrounding thermal and atmospheric condition. Typically, the metabolic rate for a normal adult with a surface area of 1.8 m\(^2\) at rest (seated and quiet) is evaluated at 1.0 met or an equivalent of 60 W/m\(^2\) (Auliciems & Szokolay, 2007).

The Mechanical Work deals with the external mechanical efficiency \(\eta\) of the human body, in other words, it can be defined as the ratio \(W/M\), with a range of 0 to 0.2; so a human body is considered as a mechanical system with low efficiency (Butera, 1998).

Heat Loss by Evaporation is similar to the heat transfer by convection, but it requires an initial change of state from liquid to vapor at the skin surface in addition to the study of the vapor boundary layer at the skin then into the ambient air. Also, the evaporation is considered a cooling mechanism. So, it plays a significant role in the body's heat balance especially if the ambient temperature is continuously increasing, or when the body is gaining heat from its environment. Also, evaporation heat losses increase at high activity levels when the metabolic heat production rises. This is illustrated in Figure 3.2 (Fanger, 1973). In order to maintain thermal comfort when the ambient temperature is lower the higher the activity level.
Figure 3.2: Evaporative heat loss as a function of the activity level for persons in thermal comfort (Fanger, 1973).

The Heat Transfer by Radiation term describes the net exchange of radiant energy between two bodies across an open space. Everybody emits electromagnetic radiation, the intensity of which is a function of the fourth power of its absolute temperature $T$. The skin, whose temperature may be between 30 and 35°C (303 and 308 K), emits such radiation, which is in the infrared zone. Moreover, it receives the radiation emitted by neighboring surfaces. The thermal flow exchanged by radiation, $R$ (in W/m²), between the body and its surroundings may be described by the following simplified expression (Larry, 1997):

$$R = f_r e_{sk} h_r (T_c - T_r), \quad \text{W/m}^2$$  \hspace{1cm} (3.3)

Where,

$T_r =$ Radiation temperature, °C

$h_r =$ Linearized coefficient of heat exchange by radiation, equal to:
\[
    h_r = 5.67 \times 10^{-8} \times 4 \left( \frac{T_{cl} + T_r}{2} + 273 \right)^3, \quad (m^2K)/W
\]

\( \varepsilon_{sk} = \) Coefficient of skin emissivity, its approximate value falls between 0.95 and 0.97.

The Convection Heat Transfer term is the transfer of heat between the skin and the air surrounding it. If the skin temperature, \( T_{sk} \), in units of degrees Celsius (°C), is higher than the air temperature (\( T_a \)), the air in contact with the skin is heated and consequently rises. Air movement, also known as free convection, is thus established at the skin surface of the body. This heat transfer becomes greater if the ambient air passes across the skin at a certain speed: this is termed forced convection. The heat flow exchanged by convection, \( C \), in units of watts per square meter (W/m\(^2\)), can be estimated by (Larry, 1997);

\[
    C = h_{cl} (T_{sk} - T_{cl}) = \frac{T_{sk} - T_{cl}}{R_{cl}}, \quad W/m^2
\]

Where \( h_c \) is the coefficient of convection (W/°C m\(^2\)), which is a function of the difference between \( T_{sk} \) and \( T_a \) in the case of natural convection, and of the air velocity \( V_a \) (m/s) in forced convection; \( h_{cl} \) and \( T_{cl} \) are the factors by which clothing reduces convection heat exchange and are defined as clothing permeability index, W/(m\(^2\)K) and external temperature of the clothing, °C respectively.

The Conduction Heat Transfer depends on thermal conductivity of materials contacting directly with the skin and the surroundings. In other words, it is the temperature difference between the body surface and the object that is in direct contact with the body (i.e. clothing). The rate of conduction is also subject to the insulation value of the cloth protecting the body is inside.
3.3 Thermal Comfort Models

The estimation of comfort requires a scientific model of the correlation between one or more climatic factors and the resulting comfort sensation that would be experienced by someone. As humans are often not the most logical or reliable of test subjects, such an association is difficult to experimentally determine. Consequently, most models are established on climatic data of large numbers of people subjected to many diverse conditions.

The central objective of comfort models is to offer a single index that incorporates all the significant comfort conditions – in order that two circumstances with dissimilar conditions, but with the same index, would result in a very similar comfort sensation (CARBSE, CEPT University, 2013). There have been a number of indices recommended with a varying amount of complication and suitability. These range from simple linear equations relating ambient air temperature to the ambient wet bulb temperature, to complex algorithms that endeavor to calculate the impact of all the environmental and physiological factors described in the preceding sections. The most intricate is not normally the most precise and the simplest are not usually the easiest to use.

Among the range of models, only four are discussed here: the simple Thermal Neutrality Model, the Adaptive Model and the most complex Fanger’s Predicted Mean Vote and Percentage of People Dissatisfied, and the Pierce Two Node Model.

3.3.1 Thermal Neutrality Model

Thermal Neutrality (Tn) describes the air temperature at which, typically, a large sample of people would express a sensation of neither hot nor cold. This temperature is
affected by both the average annual climate and seasonal fluctuations within it. Experiments have found that \( T_n \) correlates well with the indoor average dry bulb temperature, such that the relationship can be given by (de Dear & Brager, 1998):

\[
T_n = 17.8 + 0.31 \cdot T_m \tag{3.6}
\]

Also called thermoneutrality, the condition in which the thermal environment of a homeothermic is such that its heat production (metabolism) is not increased either by cold stress or heat stress. The range of temperature in which this minimum occurs is called the “zone of thermal neutrality”. For humans, this zone is 29 °C – 31 °C. These are neutrality temperatures for people at sedentary work, in their normal environment, wearing the clothing of their choice and are valid for \( T_n \) between 18 °C and 30 °C. The comfort limits are defined as \( T_n \pm 2.5 \, ^\circ C \) (de Dear & Brager, 1998).

3.3.2 Adaptive Model

Thermal comfort is tough to describe and even tougher to accomplish. The most common complaint about workplace environments is that they are too cold. This would be a fairly simple problem to fix if the second most common complaint weren’t that the same spaces are too hot.

According to ASHRAE Standard 55 (ASHRAE, 2005), which defines thermal comfort in commercial buildings, success means that an environment meets the needs of 80% of occupants. The conventional way to meet that threshold is to create a highly predictable, controlled environment using the energy-intensive mechanical equipment.

However, concerns around energy efficiency and indoor air quality have led to more interest in the concept of adaptive thermal comfort. Adaptive comfort models add a
bit more human manners to the mix. They assume that, if changes take place in the thermal environment to produce stress/strain, then people will commonly alter their behavior and act in a way that will reestablish their comfort. Table 3.5 enlists typical adaptive behaviors. Such actions could comprise reducing amount of insulating/clothing, reducing activity levels or even changing locations to an area of fresh air. The principal influence of such models is to escalate the range of conditions that designers can consider as comfortable.

Table 3.5: The effect of adaptive behaviors on optimum comfort temperatures. Taken from BRE Adaptive Thermal Comfort Models [Oseland, 1998].

<table>
<thead>
<tr>
<th>Behavior</th>
<th>Effect</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jumper/Jacket on or off</td>
<td>Changes Clo by ± 0.35</td>
<td>± 2.2 K</td>
</tr>
<tr>
<td>Tight fit/Loose fit clothing</td>
<td>Changes Clo by ± 0.26</td>
<td>± 1.7 K</td>
</tr>
<tr>
<td>Collar and tie on or off</td>
<td>Changes Clo by ± 0.13</td>
<td>± 0.8 K</td>
</tr>
<tr>
<td>Office chair type</td>
<td>Changes Clo by ± 0.05</td>
<td>± 0.3 K</td>
</tr>
<tr>
<td>Seated or walking around</td>
<td>Varies Met by ± 0.4</td>
<td>± 3.4 K</td>
</tr>
<tr>
<td>Stress level</td>
<td>Varies Met by ± 0.3</td>
<td>± 2.6 K</td>
</tr>
<tr>
<td>Vigor of activity</td>
<td>Varies Met by ± 0.1</td>
<td>± 0.9 K</td>
</tr>
<tr>
<td>Different postures</td>
<td>Varies Met by ± 10%</td>
<td>± 0.9 K</td>
</tr>
<tr>
<td>Consume cold drink</td>
<td>Varies Met by -0.12</td>
<td>- 0.9 K</td>
</tr>
<tr>
<td>Consume hot drink/food</td>
<td>Varies Met by +0.12</td>
<td>+ 0.9 K</td>
</tr>
<tr>
<td>Operate desk fan</td>
<td>Varies Vel by +2.0m/s</td>
<td>± 2.8 K</td>
</tr>
<tr>
<td>Operate ceiling fan</td>
<td>Varies Vel by +1.0m/s</td>
<td>± 2.2 K</td>
</tr>
<tr>
<td>Open window</td>
<td>Varies Vel by +0.5m/s</td>
<td>± 1.1 K</td>
</tr>
</tbody>
</table>

As described earlier thermal comfort depends on far more than just air temperature it also includes the environmental factors of mean radiant temperature (the average temperature of the surfaces surrounding an object or individual), relative humidity, and airflow velocity. And it depends on highly variable personal factors such as the amount of clothing being worn, a person’s resting metabolic rate, and the level of physical activity. Many of these factors can be adjusted by individuals one can put on a sweater, for example,
but the complex interaction of all these factors can add up to a significant challenge for comfort designers.

Adaptive thermal comfort widens our comprehension of the human comfort zone by taking into account the ways that people’s perceptions of their environment change based on seasonal expectations of temperature and humidity along with their capacity to control the conditions in a space. In a hot environment, for example, people may be more accommodating of warmer temperatures if they are assured of adequate inflow of fresh air. This not only offers breezes, which reduce the apparent temperature, it also positions occupants to familiar conditions, improving productivity and overall occupant satisfaction. Mounting cooling devices such as fans near workstations also provides workers more flexibility over the conditions in their immediate surroundings.

By way of the fact that they are governed by human behavior so much, adaptive models are usually established on wide-ranging surveys of thermal comfort conditions. Research shows that as long as people are given the avenues to regulate their local environment significantly increases the percentage of satisfied occupants and makes them more considerate of occasional periods of poor performance.

3.3.3 Fanger’s Model

Fanger (1970) defined thermal comfort as “The condition of mind which expresses satisfaction with the thermal environment”. The Predicted Mean Vote (PMV) presents a thermal sensation scale calibrated in the range from Cold (-3) to Hot (+3), originally established by Fanger and later accepted as an ISO standard. The original data was collected by exposing a number of people; apparently many thousands of Israeli soldiers;
to different conditions within a climate chamber and having them select a position on the thermal scale that best described their comfort sensation. A scientific model of the interrelationship between the environmental and physiological factors considered was then derived from the data.

From the PMV result, the Predicted Percentage of Dissatisfied people (PPD) can be established. As PMV moves away from the neutral (PMV = 0) position in either direction, PPD number rises. The maximum number of people unhappy with their comfort conditions is a maximum 100% and, since we can certainly not satisfy all of the people all of the time, the minimum number even in what would be considered acceptably comfortable conditions is 5%. In some studies, the researchers chose the thermal conditions, and participants recorded how hot or cold they felt, using the seven-point ASHRAE thermal sensation scale shown in Figure 3.3. In other studies, participants controlled the thermal environment themselves, adjusting the temperature until they felt thermally ‘neutral’ (i.e. neither hot nor cold; equivalent to voting ‘0’ on the ASHRAE thermal sensation scale).

<table>
<thead>
<tr>
<th>Value</th>
<th>Thermal Scale</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>

Figure 3.3: ASHRAE Thermal Sensation Scale (ASHRAE, 2005)
The PMV equation for thermal comfort is a steady-state model. It is a practical equation for calculating the typical vote of a large number of people on a 7 point scale (-3 to +3) of thermal comfort. The calculation uses the steady state heat balance of the human body and develops a relationship between the thermal comfort vote and the degree of stress or load on the body (e.g. sweating, vasoconstriction, vasodilation) caused by any deviation from equilibrium. The larger the heat load, the further the comfort vote will deviate from the neutral (0) position.

The derivative of the heat load utility function is estimated by subjecting adequate people to different conditions to fit a curve. The ISO (International Standards Organization) Standard 7730 (ISO 1984), "Moderate Thermal Environments - Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort," uses limits on PMV as an explicit definition of the comfort zone.

The PMV model is only suitable for acclimatized humans exposed for a long period to constant climate conditions at a constant metabolic rate. Conservation of energy leads to the following heat balance equation:

\[ H - E_d - E_{sw} - E_{re} - L = R + C \] (3.7)

Where: \( H = \) internal heat production, \( E_d = \) heat loss due to water vapor diffusion through the skin, \( E_{sw} = \) heat loss due to sweating, \( E_{re} = \) latent heat loss due to respiration, \( L = \) dry respiration heat loss, \( R = \) heat loss by radiation from the surface of a clothed body, \( C = \) heat loss by convection from the surface of a clothed body.

The equation is expanded by replacing each term with a function derivable from basic physics principles as determined below (Fountain & Huizenga, 1995).
\[ H = M - W \]  

(3.8)

\[ E_d = 3.05 \times 10^{-3} (256T_{sk} - 3373 - P_a) \]  

(3.9)

\[ E_{sw}, E_{rsw,req} \text{(for comfort)} = 0.42 \cdot W - 58.15 \]  

(3.10)

\[ L = 0.0014M(34 - T_a) \]  

(3.11)

\[ E_{re} = 1.72 \times 10^{-5} - 5M(5867 - P_a) \]  

(3.12)

\[ K = \frac{f_{cl}}{0.155f_{cl}} \]  

(3.13)

\[ R = 3.96 \times 10^{-8} f_{cl} [ (T_{cl} + 273)^4 - (T_r + 273)^4 ] \]  

(3.14)

\[ C = f_{cl} h_c (T_{cl} - T_a) \]  

(3.15)

Where; Pa is partial pressure of water vapor in air (kPa), \( I_{cl} \) is intrinsic clothing insulation (clo or \( \text{m}^2 \cdot \text{°C} \cdot \text{W}^{-1} \)). The unit of all above components is \( \text{Wm}^{-2} \).

All of the functions have quantifiable terms with the exception of clothing surface temperature and the convective heat transfer coefficient which depends on each other. To equation is solved by assuming an initial value of clothing temperature, from which the convective heat transfer coefficient is then computed, and a new clothing temperature calculated etc. A number of iterations are then executed until both are known to a satisfactory measure. If the body is assumed not to be in thermal balance, the heat equation can be re-written as:

\[ L = H - E_d - E_{sw} - E_{re} - R - C \]  

(3.16)

Where: L is the thermal load on the body.
Fanger’s PMV model is based on thermoregulation and heat balance theories. According to these theories, the human body employs physiological processes (e.g. sweating, shivering, regulating blood flow to the skin) in order to maintain a balance between the heat produced by metabolism and the heat lost from the body. In extreme thermal conditions, this regulation is necessary for the body to function properly. In mild climates, it is very unlikely that temperatures associated with serious bodily dysfunction will occur, but thermoregulation is still used to maintain a comfortable heat balance (ASHRAE, 2001).

Maintaining this heat balance is the first condition for achieving a neutral thermal sensation. However, (Fanger, 1970) noted that “man’s thermoregulatory system is quite effective and will, therefore, create heat balance within wide limits of the environmental variables, even if comfort does not exist”. To be able to predict conditions where thermal neutrality would occur, (Fanger, 1967) investigated the body’s physiological processes when it is close to neutral. Fanger determined that the only physiological processes influencing heat balance in this context were sweat rate and mean skin temperature and that these processes were a function of activity level.

(Fanger, 1967) used data from a study by McNall, Jaax, Rohles, Nevins, and Springer (1967) to derive a linear relationship between activity level and sweat rate. College-age participants in this study were exposed to different thermal conditions while wearing standardized clothing, and voted on their thermal sensation, using the ASHRAE scale. The linear relationship was formed from those participants (n=183) who stated that they felt thermally neutral (i.e. voted ‘0’) for a given activity level.
(Fanger, 1967) substituted these two linear relationships into heat balance equations, to create a ‘comfort equation’. The comfort equation describes all combinations of the six PMV input variables that result in a neutral thermal sensation. This equation was then validated against studies by Nevins, Rohles, Springer and Feyerherm 1966 and McNall et al. 1967, in which college-age participants rated their thermal sensation in response to specified thermal environments. The air temperature where participants were thermally neutral in these studies showed good agreement with the predictions made by the comfort equation.

The comfort equation predicts conditions where occupants will feel thermally neutral. However, for practical applications, it is also important to consider situations where subjects do not feel neutral. By combining data from Nevins et al 1966, McNall et al. (1967) and his own studies, Fanger in 1970, used data from thousands of participants to expand the comfort equation. The resulting equation described thermal comfort as the imbalance between the actual heat flow from the body in a given thermal environment and the heat flow required for optimum (i.e. neutral) comfort for a given activity. This expanded equation related thermal conditions to the seven-point ASHRAE thermal sensation scale, and became known as the PMV index as expressed in equation (3.17):

$$\text{PMV} = (0.303 \cdot e^{-0.036 \cdot M + 0.028}) \cdot L$$

(3.17)

Where: M is the metabolic rate.

Fanger, in 1970 also established an associated index, so-called the Predicted Percentage Dissatisfied (PPD). This index is predicted from the PMV model and calculates the percentage of people likely to be displeased with a given thermal climate. The PMV
and PPD form a U-shaped relationship (see equation 3.18), where percentage dissatisfied increases for PMV values above and below zero (thermally neutral).

\[
PPD = 100 - 95 \cdot e^{-(0.03353PMV^4 + 0.2179PMV^2)}
\]  

The PMV index is mathematically complex to compute, so Fanger (1970) provided look-up tables to help practitioners determine appropriate thermal conditions. Information from these tables and graphical representations of comfort conditions is also provided in modern thermal comfort standards (e.g. ASHRAE, 1992; ISO, 1994). In recent years, computer programs have been developed to calculate PMV, and programming code is provided in ISO Standard 7730 (ISO, 1994).

Thermal comfort standards employs the PMV model to suggest tolerable thermal comfort conditions. These thermal conditions should guarantee that at least 90% of occupants feel thermally content. Fangers’ model has limitation related to: PMV has been established for the homogenous condition, the distinction between local and whole-body thermal comfort.

### 3.3.4 Pierce Two Node Model

The Pierce Two-Node model was developed at the John B. Pierce Foundation at Yale University. The model has been continually expanding since its first publication in 1970 (Gagge et al., 1970). The most recent version on the model appears in the 1986 ASHRAE Transactions (Gagge et al., 1986).

The Pierce model thermally lumps the human body as two isothermal, concentric compartments, one representing the internal section or core (where all the metabolic heat
is assumed to be generated and the skin comprising the other compartment). This allows the passive heat conduction from the internal human body to the skin to be accounted for. The boundary line between two compartments changes with respect to skin blood flow rate per unit skin surface area (SKBF in L/h•m²) and is described by alpha – the fraction of total body mass attributed to the skin compartment (Doherty and Arens, 1988).

\[ \alpha = 0.0417737 + 0.7451832/(SKBF + 0.585417) \]  

(3.19)

Furthermore, the model takes into account the deviations of the core, skin, and mean body temperature weighted by alpha from their respective set points. Thermoregulatory effector mechanisms (Regulatory sweating, skin blood flow, and shivering) are defined in terms of thermal signals from the core, skin and body (Doherty and Arens, 1988).

The latest version of the Pierce model (Fountain, Marc. Huizenga, Charlie, 1993) discusses the concepts of SET* and ET*. The Pierce model converts the actual environment into a "standard environment" at a Standard Effective Temperature, SET*. SET* is the dry-bulb temperature of a hypothetical environment at 50% relative humidity for subjects wearing clothing that would be standard for the given activity in the real environment. Furthermore, in this standard environment, the same physiological strain, i.e. the same skin temperature and skin wettedness and heat loss to the environment, would exist as in the real environment. The Pierce model also converts the actual environment into an environment at an Effective Temperature, ET*, that is the dry-bulb temperature of a hypothetical environment at 50% relative humidity and uniform temperature (Ta = Tr)
where the subjects would experience the same physiological strain as in the real environment.

In the latest version of the model, it is suggested that the classical Fanger PMV be modified by using ET* or SET* instead of the operative temperature. This provides a new index PMV* which is suggested for dry or humid environments. It is also submitted that PMV* is very receptive to the variations in vapor permeation effectiveness of the occupants clothing.

Besides PMV*, the Pierce Two Node Model also uses the indices TSENS and DISC to predict thermal comfort. TSENS is the standard index used by the Pierce foundation, and depends on the mean body temperature. DISC is described as the comparative thermoregulatory strain that is required to establish a state of comfort and thermal equilibrium. DISC is dependent on the heat stress and strain in hot climates and equal to TSENS in cold climates.

In conclusion, the Pierce Model applies four thermal comfort indices namely; PMVET-a function of ET*, PMVSET- a function of SET*, TSENS and DISC.

### 3.3.5 Other Human Comfort Indices

The indicator of human thermal comfort is in principle called the thermal comfort index. A thermal comfort index method uses a model that provides a single number that represents the degree of discomfort caused by an environment. The model is based upon research and integrates the relevant factors of the environment (temperatures, air flows, humidity, etc.) surrounding a person in a way representing the comfort response of the person.
Some number of comfort indices have been deliberated and considered for the
design of comfort in the mining environment. Below are the most commonly used thermal
comfort indices:

3.3.5.1 Effective Temperature (ET)

The index establishes a link between the identical state of the organism’s
thermoregulatory capacity (warm and cold perception) as well as differing temperature and
humidity of the surrounding environment. Using this index, it is possible to obtain the
effective temperature felt by the human organism for certain values of meteorological
parameters such as air temperature, relative humidity of the air, and wind speed, which
determine the thermal exchange between the organism and the environment. This is still
being used in Germany, where medical check-ups for subjects working in the heat are
decided on by prevailing levels of ET, depending on metabolic rates

\[
ET = 37 - \frac{37-T}{0.68-0.0014\times RH+\frac{1}{1.76+1.4\times v^{0.75}}} - 0.29\times T \times (1 - 0.01\times RH) \tag{3.20}
\]

Where: v is wind speed (in m s\(^{-1}\)) at 1.2 m above the ground.

Yaglou in 1947 already noted that the ET overestimates the effect of humidity,
especially at lower temperatures. Smith (1955) found that the relationship is not linear and
that the P4SR index gives a better correlation with comfort votes. Glickman et al. (1950)
also found that ET overestimates the effect of humidity under both cool and comfortable
conditions.
3.3.5.2 The Wet Bulb Globe Temperature (WBGT)

The wet bulb globe temperature is calculated using a formula that takes into account air temperature, the speed of air movement, radiant heat from hot objects, sunshine and body cooling due to sweat evaporation. The wet bulb globe temperature (WBGT) is calculated by using the following equations.

- For outdoors with direct sun exposure:

\[
WBGT = 0.7 \times Temp_{\text{wet bulb}} + 0.2 \times Temp_{\text{globe}} + 0.1 \times Temp_{\text{air}}
\]  
(3.21)

- For indoors or outdoors without direct sun exposure:

\[
WBGT = 0.7 \times Temp_{\text{wet bulb}} + 0.3 \times Temp_{\text{globe}}
\]  
(3.22)

Where:

\(Temp_{\text{wet bulb}}\): The natural wet bulb temperature measured by using a thermometer whose bulb is covered with wet cotton cloth and is cooled by the natural air movement.

\(Temp_{\text{globe}}\): Temperature measured using a black globe thermometer and

\(Temp_{\text{air}}\) is Temperature measured using a conventional thermometer. All temperatures are to be expressed in °C.

Parsons (2006) considers its use in global applications and presents a method for integrating clothing into the index. The size of the globe (150 mm diameter – ISO 7243) is often considered, as smaller globes than specified are often used (typically 40mm) as they are more convenient and respond more rapidly. Nevertheless, smaller globes will be impacted less by radiation and more by air velocity and air temperature. Depending on conditions, unless corrected, WBGT values measured in hot environments with high
radiant fields (e.g. in the vicinity of hot furnaces or molten metal) will, therefore, tend to be lower than those that would be obtained with a correctly specified globe. It should also be noted that the wet bulb quoted is ‘natural’ i.e. it is unshielded from the radiant field (and from air movement) and so could exceed the air temperature value, the probe for which should be shielded. With normal wet and dry bulb measurement, the wet bulb does not exceed the dry bulb value, (Youle, 2005).

Recent studies on the evaluation of the WBGT index include Malchaire (2006); Brake and Bates (2002) and Miller and Bates (2006). In the latter two studies, the ‘Thermal Work Limit’ (TWL) index is introduced and tested against the WBGT in mining environments.

Despite recent discussion of its limitations in underestimating the effect of wind speed (Miller and Bates, 2007) and its inability to measure the effect of the other two important heat stress factors, metabolic rate and clothing effect (Parsons, 2006), the WBGT remains a valid heat index for managing occupational heat stress in a convenient procedure.

Supplementary methods have been devised to address the limitations by standardizing wind speed, categorizing metabolic rate by types of work, and setting up clothing adjustment values for major work uniforms (Ashley et al., 2008; Bernard, 1999).

WBGT was found to be limited in evaluating potential heat stress because of two main reasons:

- It doesn’t take into account the effect of different type of clothing for workers; and
• The inconvenience of measuring $T_{globe}$

Calculation of WBGT involves measuring $T_{globe}$ using a thermometer surrounded by a 6 inch blackened sphere, which is inconvenient and simply not practical to use under many working conditions.

### 3.3.5.3 Thermal Work Limit (TWL)

Thermal Work Limit (TWL) is an integrated measure of the dry bulb temperature, wet bulb temperature, wind speed and radiant heat. The TWL predicts the maximum level of work that can be carried out in a given environment, without workers exceeding a safe core body temperature (38.2°C or 100.8°F) and sweat rate (< 1.2 kg or 2.6 lb. per hour) (Brake and Bates, 2002). The TWL is developed from published studies of human heat transfer and moisture equations through clothing. In extremely hot environments, the TWL can limit the safe work duration, thus preventing heat-related illness and providing guidelines for work/rest cycling.

The TWL model is used as an alternative to heat indices in guidelines for heat stress management in the Australian mining industry (Bell, 2012; Corleto, 2011; Taylor and O’Sullivan, 2012) and is specified as a tool to set up thresholds for workplace heat stress control in Abu Dhabi’s industrial guidelines (Abu Dhabi EHS Center, 2012). TWL gives an estimate of the tolerable safe work rate for the environmental conditions existing in a workplace. If TWL is too low then even low rates of work cannot safely be carried out continuously and extra rest breaks and other precautions are needed to ensure workers’ safety. Figure 3.4 illustrates the working zones of the TWL and recommended management interventions.
Figure 3.4: TWL working zones and recommended management interventions.

The basic purpose of the thermal work limit index is to calculate the maximum metabolic rate, in watts of metabolic heat per square meter of body surface area that can be continuously expended in a particular thermal environment, in order to keep the body
within safe physiological limits (Brake and Bates, 2002). The TWL is established by an integrated measure of the dry bulb, wet bulb, wind speed and radiant heat generated in the environment. From these variables, and taking into consideration the type of clothing worn and the acclimatization state of the workers, the TWL predicts the maximum level of work that can be carried out in a given environment, without workers exceeding a safe core body temperature of 38.2 °C (100.8 °F) and sweat rate (Miller and Bates, 2007).

Sweat rates are also determined, in order that the level of fluid replenishment necessary to inhibit dehydration can be established. The thermal work limit algorithm builds on work originated by Mitchell and Whillier, who developed an index called the “specific cooling power,” which subsequently became known as the “air cooling power” (ACP).

### 3.3.5.4 Heat index (HI)

The heat index is an index that combines air temperature and relative humidity to determine an apparent temperature: how hot it actually feels. The HI equation (Rothfusz, 1990) is derived by multiple regression analysis in temperature and relative humidity conditions from the first version of Steadman’s (1979) apparent temperature (AT). When humidity is high, the evaporation rate of water is reduced (although relative humidity is used in the formula, the term “relative” is misleading in the context of the statement). This means heat is removed from the body at a lower rate, causing it to retain more heat than it would in dry air. HI, which is widely used in the United States, is calculated as follows:
HI = -42.379 + 2.04901523T + 10.14333127R - 0.22475541TR - 6.83783 \times 10^{-3}T^2 - 5.481717 \times 10^{-2}R^2 + 1.22874 \times 10^{-2}T^2R + 8.5282 \times 10^{-4}TR^2 - 1.99 \times 10^{-6}T^2R^2 \tag{3.23}

Where:

T - Air temperature (°F)

R - Relative humidity (percentage)

\[ HI = -8.784695 + 1.61139411 \times T + 2.338549 \times RH - 0.14611605 \times T \times RH - 1.2308094 \times 10^{-2} - 1.6424828 \times 10^{-2} \times RH^2 + 2.211732 \times 10^{-3} \times T^2 \times RH + 7.2546 \times 10^{-4} \times T \times RH^2 - 3.582 \times 10^{-6} \times T^2 \times RH^2 \tag{3.24} \]

Where:

T is air temperature in °C, and RH is relative humidity rounded to its integer value in %.

HI is valid for air temperatures above 20°C and its values are categorized due to possible heat disorders in people.

**3.3.5.5 The Discomfort Index (DI)**

The DI, although it does not account directly for radiation, it is easy to use, and it is extensively used in Israel. It is suggested to adopt this index and test its applicability also by others.

\[ \text{DI} = 0.4T_w + 0.4T_a + 8.3 \tag{3.25} \]

Under DI values of 22 units, no heat stress is encountered. Between 22–24 units most people feel a mild sensation of heat; between 24–28 units the heat load is moderately heavy,
people feel very hot, and physical work may be performed with some difficulties. Above 28 units, the heat load is considered severe, and people engaged in physical work are at increased risk for heat illness (heat exhaustion and heat stroke).

### 3.4 Summary

The complicated relations of air temperature, mean radiant temperature, air velocity and humidity establishes what is called the “human thermal environment”. To accomplish an acceptable thermal environment, it is valuable to be able to predict the effect of a particular combination of thermal conditions on human occupants. So, this chapter introduced a comprehensive review of the human thermal environment, basic definitions, main factors affecting thermal comfort, human heat balance equation in terms of heat generation, and heat exchange with the environment. Furthermore, the chapter introduced and discussed the most popular and widely used comfort models to estimate local and overall sensation and comfort, Fanger’s model in terms of PMV and PPD indices, Pierce Two-Node model and the adaptive model. Finally, some important indices widely used in the comfort and thermal sensation such as WBGT, ET, DI, HI, and TWL were discussed.
CHAPTER 4: SKIN TEMPERATURE AND COMFORT, A REVIEW

4.1 Introduction

Mean skin temperature is a physiological parameter of interest for the evaluation of thermal comfort in working man. The human body controls temperature by keeping a firm balance between heat gain and heat loss (Vella & Kravitz, 2004). The skin is the principal organ for dissipating heat: the human body dissipates approximately 85% of its heat loss through the skin under normal environmental conditions (Zhang, 2003).

In steady-state and uniform thermal environments, air temperature, thermal radiation, air velocity, humidity, clothing, and activity are six well-known factors that influence the human thermal state. A steady-state thermal environment is one where the temperature does not vary with time while in non-steady climates there’s temperature variation with time. Creating a database of all possible thermal states for comfort is unfeasible as unlimited combinations of these factors exist. Except for “activity,” all the factors influence the physiological thermal state of a human being through the heat transfer processes at the skin surface.

For non-uniform thermal environments, there are many indices developed based on heat transfer principles. These include radiant temperature asymmetry, (Fanger et al. 1987); partial operative temperature (Horikoshi et al. 1990); local equivalent temperature or equivalent homogenous temperature (Tanabe et al. 1994) and (Wyon et al., 1989); local standard effective temperature (Kohri et al. 2003); local humid operative temperature, (Suzuki et al. 2003); etc.
However, when both the local heat transfer rate at the skin surface and the local physiological thermal state of the skin do not share a simple relationship, these indices are capable of assessing the local thermal state only in a limited number of conditions. There also exists a thermal comfort model that is applicable in non-uniform and transient conditions (Zhang et al. 2004). It comprises the parameters of local skin temperatures, core temperature, and their time derivatives. However, this model does not include the local heat transfer rate. Since heat transfer rate is an important factor when considering thermal environments, the effect of this factor is expected to be included in the human thermal comfort model for a non-uniform thermal environment.

This chapter presents an overview of the human skin functions that affect human comfort and human body heat regulation.

4.2 The Skin

The human body's largest organ is the skin. Skin protects body tissues against injuries and helps control body temperature by enlarging or narrowing the pores. The nerves in the skin accept the stimuli that are then deduced by the brain as touch, heat, and cold.

Skin is made up of three stratum: epidermis, dermis, and subcutaneous fatty tissue. The boundary flanked by the epidermis and dermis is very uneven and is made up of a sequence of fingerlike projections, which are smallest where the skin is thin and longest in the skin of the palms and soles (Elert, 2015). The fingerlike projections in the palms and soles are associated with rises of the epidermis, which produce ridges that are the basis for fingerprint identification (Elert, 2015).
The deepest stratum of the skin is the subcutaneous fatty tissue. It is comprised of connective tissue, blood vessels, and fat cells (Elert, 2015). This stratum connects the skin to underlying structures, insulates the body from cold, and stores energy in the form of fat (Elert, 2015).

The skin develops a shielding fence against the action of physical, chemical, and bacterial agents on the deeper tissues and encompasses the distinct end organs for the various sensations usually grouped as the sense of touch (Elert, 2015). By way of its sweat glands and blood vessels, it is central in maintaining body temperature. A square inch (6.5 square centimeters) of skin holds up to 4.5 m of blood vessels, which have as one of their tasks, the control of body temperature.

The skin varies in thickness from 0.5 mm on the eyelids to 4 mm or more on the palms and soles (Elert, 2015). The average human body has between 1.8 m² to 2.0 m² of surface area which serves as a furnace for liberating heat via radiation to lower the body temperature or as an absorber to take in radiant energy to raise the body temperature. The skin’s emissivity is around 0.97 which makes it practically perfect as a radiator and absorber of heat (Elert, 2015).

4.3 Skin Temperature and Thermal Regulation

The skin is the largest organ in the human body (Elert, 2015). It protects the body from the sun's rays. It also keeps body temperature normal (37±1 °C).

Skin temperature depends on air temperature and time spent in that environment. Such climate factors as wind velocity and humidity cause changes in skin temperature. The normal temperature of the skin is about 33°C. The flow of energy to and from the skin
determines our sense of hot and cold. Heat flows from higher to lower temperature, so the human skin will not drop below that of surrounding air, regardless of wind. If a person was to be in a hot environment and his/her skin temperature was cooler than the air, his/her skin temperature would rise. The opposite happens in a cold room and warm skin temperature. The person's temperature would decrease. Humans fight air temperature by becoming warm or cold. When warm, they sweat. When cold, they get a chill (Elert, 2015). Different parts of the body have different skin temperatures as depicted in Figure 4.1.

4.3.1 Human Response to the Thermal Environment

Humans are comfortable within a very small range of core body temperatures. Biochemical processes in the body will not function if the temperature becomes too low or too high. At very high temperatures enzymes lose their activity and at low temperatures there is inadequate energy to continue metabolic processes. When the core temperature rises above 40 °C, hyperthermia occurs, and hypothermia occurs below 35°C. Humans can tolerate extreme temperatures below 35°C or above 41°C for only very brief periods of time. To maintain internal temperature within these limits, people have developed very effective and in some instances specialized physiological responses to critical thermal stresses. These responses are designed to facilitate the conservation, production or elimination of body heat. This is achieved through finely controlled coordination of several body systems.
4.3.2 Comfort and Stress

Assessment of comfort must start with an appreciation that comfort is a state of mind (ASHRAE, 2009). It is extremely difficult to classify the many factors which affect comfort; the interaction between the physical demand imposed upon the individual, his physiological status, and his psychological attitudes must be considered in interaction with social customs, tangible perceptions and the likes (Goldman, 2007). Restricting ourselves to thermal comfort is still subjective and difficult to satisfy all individuals with a given simple environmental specification. Undeniably, thermal comfort depends on the

Figure 4.1: Skin temperatures on different parts of a nude person measured at different ambient temperatures [Olesen, 1982].
interaction between three groups of elements: environmental factors, clothing factors, and physiological factors.

Thermal comfort falls in air temperature range of 15°C to 28°C for a resting man (Goldman & Kampmann, 2007). Nevertheless, the human body has a much narrower physiological comfort range. This is the temperature range where human temperature regulation can be realized: (1) without shivering flow from the body core to the skin, and (2) without sweating to attain evaporative cooling. ASHRAE’s Standard 55, Thermal Environmental Conditions for Human Occupancy, recommends conditions that have been found experimentally “to be acceptable to at least 80 percent of the occupants within space”. It specifies the operative temperature range for occupants in typical winter clothing (0.8 to 1.2 clo) to be to 20° to 23.5°C. The preferred temperature range for occupants dressed in summer clothes (0.35 to 0.6 clo) is 22.5°C to 26°C (Goldman & Kampmann, 2007). This suggests the human comfort zone for physiological regulation of body temperature to be in a range of approximately 3.3°C. Thermal comfort outside this zone of physiological regulation from 22.2 to 25.5°C with normal indoor clothing is provided by "behavioral" temperature regulation by adding or removing clothing.

4.3.3 Human Heat Regulation

The Various human body systems must synchronize their activities to perform physical activity. These systems have the capacity to adapt when exposed to the stresses of specific environments. There are mechanisms by which the body can regulate its core temperature both at rest and during activity, as well as in both hot and cold or humid environments, along with health risks that are associated with physical activity in the
aforesaid environments (King, 2004). Through the use of its intricate temperature regulation, the human body is able to reach a state of thermal equilibrium with the surrounding environment when the variation of internal energy, $S$, at the body core level is equal to zero (Fanger, 1970). The thermal exchange between a subject and the environment is equal to the difference between metabolic heat and thermal losses due to respiration and exchanges of heat through the skin surface.

### 4.3.4 Heat Production

The food we eat is subjected to exothermic chemical reactions; these constitute the metabolic heat power, $M$. Through these processes, most of the food's chemical energy is converted into thermal energy. A portion of this thermal energy is required to preserve the human body's core at a normal temperature and to enable the body's internal organs to receive everything essential for their normal running. This rate of energy generated varies depending on the subject's size (height and weight) (Speakman, 2005). Another part of the heat produced is necessary for the mechanical activities performed by the subject. During normal activities, part of the metabolic heat produced is converted into mechanical power, $W$, which according to the first principle of thermodynamic conventions is assumed as positive when it is released in the environment.

### 4.3.5 Heat Losses

When air is inhaled during respiration its temperature and humidity are at different levels with respect to the core. Also, the body's internal heat is transferred relative to the level of activity, to the external environment by means of convective ($C_{res}$) and evaporative ($E_{res}$) exchanges. Consequently, respiratory heat losses depend on the level of an action
executed by the subject and the temperature and humidity of the air in the environment. Respired vapor Loss, (Eres) is comprised of latent respiration heat loss ($E_{rel}$) and convective or sensible respiration heat Loss (Erec). Evaporative heat Loss from Skin Surface (Esk), which is made of evaporative Heat Loss by Skin Diffusion ($E_{dif}$), and heat loss due to regulatory sweating ($E_{rsw}$) (Glen & Ollie, 2013).

The human body external surface is characterized by thermo-conditions that are mostly dissimilar from those of the neighboring environment. This prompts thermal exchanges between the subject and environment. These interactions are in the form of sensible heat losses: by convection (C), radiation (R), and conduction (K) and latent heat losses owing to the evaporation of the sweat, (E) (Hensen, 2004). Convective heat exchange depends on the relative air velocity, $v_{ar}$, and on the difference between the clothed surface temperatures, $t_{cl}$, and the air temperature, $T_a$. Radiation heat exchange depends on the difference between the clothed surface temperature, $t_{cl}$, and the mean radiant temperature, $T_r$. Convective and radiative heat exchanges depend on the thermal insulation of clothing, $I_{cl}$. The clothed surface temperature can be expressed as a function of the clothing's thermal insulation, $I_{cl}$, and of the mean skin temperature, $Tsk$ (Pozos et al., 2001). Conductive heat exchange is usually considered as insignificant compared to convection and radiation. Lastly, evaporative heat exchange through sweating depends on the clothing's evaporative resistance, on the skin's wetness and on the difference between the water vapor.

Figure 4.2 establishes the interrelationships between the physiological systems that will produce heat and the environmental and physiological systems that will cause a
decrease in heat loss. The figure demonstrates the interaction of skin and core temperatures relative to internal and external factors. It reveals that to sustain core temperature involves a balancing act between heat loss and heat production. It also establishes the interdependence among core temperature, skin temperature, and the various climate and physiological factors associated with thermal comfort regulation. The figure describes thermoregulation in its simplest form. This is illustrated in the conduction and radiation processes which can cool or heat a body. The body is in a state of thermal equilibrium with its environment when it loses heat at exactly the same rate as it gains heat (Glen & Ollie, 2013).

![Figure 4.2: Balance between heat production and heat loss mechanisms. Carb: carbohydrates; Prot: proteins; Con: conduction; Rad: radiation; Vap: evaporation [Pozos et al., 2007].](image-url)
4.4 Summary

According to ASHRAE-55, thermal comfort has been defined as the condition of mind which illustrates satisfaction with the thermal environment, and thermal sensation is related to heat balance between the human body and its ambient thermal condition. Depending on the heat transfer, via heat gain or loss, the thermoregulation system in a human brain regulates skin temperature to sustain a constant core body temperature of 36.5°C. In Wang’s study, a human body reacts via shivering when conditions are cold, in order to generate internal heat, and via sweating, when it is hot, to generate an evaporative cooling effect on the skin. However, in the range of a moderately warm to a cool condition (between 18°C and 33.5°C), the thermoregulation system controls skin temperature through vasodilatation and vasoconstriction to maintain a thermal comfort. This physiological principle illustrates that skin temperature has considerable potential for assessing thermal comfort conditions, depending on temperature values.
CHAPTER 5: MODEL DEVELOPMENT PROCESS

5.1 Background

Heat stress indices based on the heat balance equation use either a fixed mean skin temperature or a prediction model, which incorporates some or all physical factors of the thermal environment as well as the clothing insulation and the metabolic rate. A fixed value is easy to use, however, in situations with intermittent exposure to heat, this can result in severe over- or under-estimations in the heat balance equation. The model used in the Predicted Heat Strain (ISO 7933-2004) is considered to offer the best prediction so far as it is valid for a wide range of conditions (Mehnert et al., 1999).

In this study, the estimation of mean skin temperature is done using the equation developed by Hettinger, et al, 1986. The equation, taken from Mairiaux et al. (1995) is as follows:

\[ T_{sk} = 30 + 0.138 T_a + 0.254 P_a - 0.57 V_a + 0.0128 M - 0.553 R_{cl} \]  

(5.1)

This chapter presents the model development process. It illustrates how the thermal comfort of miners underground can be assessed by using the criteria of the ISO 7933 (1989 and 2004). The boundary limits of thermal comfort were determined by the maximum sweat rate criteria, the maximum skin wettedness criteria, and the maximum dehydration criteria. These indices were predicted for underground conditions with air temperatures varying between 10 °C and 50 °C and one of the other parameters varying in the ranges indicated in Table 5.1.
Table 5.1: Range of variation and normal values of the climatic parameters during the simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Constant value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Humidity, RH (%)</td>
<td>50-100</td>
<td>50, 60, ..., 100</td>
</tr>
<tr>
<td>Mean Radiant Temperature (tr=ta), (°C)</td>
<td>10-40</td>
<td></td>
</tr>
<tr>
<td>Air Velocity, va (m/s)</td>
<td>0-4</td>
<td>0, 1, 1.5, ..., 4</td>
</tr>
<tr>
<td>Clothing Insulation (clo)</td>
<td>0-1</td>
<td>0.093</td>
</tr>
<tr>
<td>Metabolic rate, M (W/m²)</td>
<td>200-340</td>
<td>250, 300</td>
</tr>
</tbody>
</table>

5.2 Introduction

The International Standards Organization (ISO) has formed an integrated series of international standards for the assessment of human responses to thermal environments. These include standards for the assessment of thermal comfort, heat stress, and cold stress. For hot environments a three-tier approach is taken which involves a simple thermal index, wet bulb globe temperature (WBGT), that can be used for monitoring and control of hot environments (ISO 7243, 1989); a rational index, required sweat rate (SWreq), which involves an analysis of the heat exchange between a worker and the environment (ISO 7933, 2004); and a standard for physiological measurement which can be used in the establishment of personal monitoring systems of workers exposed to hot environments (ISO 8996, 2004).

The simple index provides a first stage analysis and can confirm whether or not there is likely to be an unacceptable thermal strain. Where a detailed analysis is required then ISO 7933 provides an analytical method that can provide a more extensive assessment and interpretation leading to recommendations for improvement to the working environment. Where a method needs to be confirmed, or conditions are beyond the scope of ISO 7243 and ISO 7933, then ISO 9886 provides guidance on physiological measurements and interpretation. This would be used in extreme environments where responses of individuals
are required to ensure health and safety or in the case where personal protective equipment (PPE) is worn which is beyond the scope of ISO 7243 and ISO 7933.

This work will tap into the ISO systems to develop an analytical approach (Appendix D) to provide cover to almost all exposures to hot environments in hot and humid mines.

5.3 Principles in the Method of Assessment

The method of evaluation and interpretation calculates the thermal balance of the body from the parameters of the thermal environment: air temperature, $T_a$; mean radiant temperature, $T_r$; partial vapor pressure, $P_a$; air velocity, $V_a$; these parameters are estimated according to ISO 7726; the physical characteristics of the miners exposed to these working circumstances: The metabolic rate, $M$, estimated on the basis of ISO 8996; the clothing thermal characteristics estimated on the basis of ISO 9920. A constant clo value of 0.093 is used for this assessment. This is equivalent to the miners’ uniforms degree of insulation.

5.4 The Thermal Balance of the Miners’ Calculation Steps

The thermal balance equation of the body may be written as:

$$S = M - (C + R + B + E + K + W), \quad W/m^2$$

(5.2)

This equation expresses the internal heat production of the body, which corresponds to the metabolic rate ($M$) minus the effective mechanical power ($W$), is balanced by the heat exchanges in the respiratory tract by convection and evaporation ($B$), as well as by the heat exchanges on the skin by conduction ($K$), convection ($C$), radiation ($R$), and evaporation ($E$), and by the eventual balance, heat storage ($S$), accumulating in the body. The different terms of Equation (5.11) are reviewed in terms of the principles of calculation.
5.4.1 Metabolic rate, $M$

The estimation of the metabolic rate is described in ISO 8996. In this study, it is assumed that miners work underground under moderate to severe physical labor intensity, so 200, 220, 240, 260, 280, 300 W/m$^2$ and excessive physical strength of 320 and 340 W/m$^2$ are selected as the amount of miners’ metabolic values for the analysis.

5.4.2 Effective mechanical power, $W$

In most industrial situations, the effective mechanical power is small and can be neglected.

5.4.3 Heat flow by respiration, $B$

The heat flow by respiratory convection may be expressed, in principle, by the equation: The flux density of respiratory heat exchange is proportional to the difference between wet bulb temperatures of inhaled and exhaled air:

$$B = \frac{m(S_{out} - S_{in})}{F_{Du}} = 1.7 \times 10^{-6} \times M(S_{out} - S_{in}), \text{ W/m}^2$$  \hspace{1cm} (5.3)

$S_{out} - S_{in}$ = Difference between the sigma-heat of inhaled and exhaled air, J/kg

$m = 1.7 \times 10^{-6} \times M F_{Du}$ = stream of mass the of inhaled air proportional to the metabolic heat production. $M$ is the metabolic rate. $F_{Du} =$ Surface area of the whole human body, m$^2$.

Knowing the body height $h$ and the mass $k$, the surface area can be obtained from the DuBois formula (Fanger 1974):

$$F_{Du} = 0.202 m^{0.425} h^{0.725}, \text{ m}^2$$  \hspace{1cm} (5.4)
5.4.4 Heat flow by conduction, K

This study did not take into account the heat flow by conduction. According to field measurement and analytical studies, conduction heat loss and mechanical work attribute a relatively small portion to the underground mine environment (McPherson, 1992).

5.4.5 Heat flow by convection at the skin surface, C

The reduction terms in respect to the clothing factor for sensible \( F_{cls} \) and latent heat \( F_{cll} \) exchange can be calculated as follows.

\[
F_{cls} = \frac{1}{1+(h_c+h'_r)R_{ele}} \tag{5.5}
\]

\[
F_{cll} = \frac{1}{1+0.92h_cR_{ele}} \tag{5.6}
\]

The heat flow by convection at the skin surface may be expressed by the equation:

\[
C = h_{cl} (T_{sk} - T_{ct}) = \frac{T_{sk} - T_{cl}}{R_{ct}}, \quad W/m^2 \tag{5.7}
\]

Where:

\( h_{cl} \) = Clothing permeability index, W/(m²K), \( T_{cl} \) = External temperature of the clothing, \(^\circ\)C, \( R \) = Thermal resistance of the clothing, (m²K)/W. \( T_{sk} \) is the mean skin temperature.

Thermal resistance is the inverse of clothing permeability index.

\[
C = h_{cf}f_{ct}(T_{ct} - T_{a}), \quad W/m^2 \tag{5.8}
\]

\( f_{ct} \) = clothing factor (associated with the skin surface available for heat exchange). \( h_c \) = heat absorption coefficient related to the airflow velocity.
5.4.6 Heat flow by radiation at the surface of the skin, $R$

The heat flow by radiation may be expressed by the equation:

$$R = f_r \varepsilon_{sk} h_r (T_{cl} - T_r), W/m^2$$  \hspace{1cm} (5.11)

Where,

$T_r =$ radiation temperature, °C,  $\varepsilon_{sk} =$ Coefficient of skin emissivity, its approximate value falls between 0.95 and 0.97, and the coefficient of heat exchange by radiation is derived from the formula:

$$h_r' = f_r \varepsilon_{sk} h_r, \hspace{0.5cm} W/(m^2K)$$ \hspace{1cm} (5.12)

Thermal resistance of the separating layer Ra is expressed as:

$$R_a = \frac{1}{h_c + h_r}, (m^2K)/W$$ \hspace{1cm} (5.13)

$$R_{cl} = R_c - R_a \left(1 - \frac{1}{f_{cl}}\right), (m^2K)/W$$ \hspace{1cm} (5.14)

$$T_{cl} = T_{sk} - CR_{cl}, \hspace{0.5cm} ^\circ C$$ \hspace{1cm} (5.15)

$h_r =$ linearized coefficient of heat exchange by radiation, equal to:

$$h_r = 5.67 \times 10^{-8} \times 4 \left(\frac{T_{cl} + T_r}{2} + 273\right)^3, (m^2K)/W$$ \hspace{1cm} (5.16)

$$f_r = \frac{F_r}{F_{Du}}$$ \hspace{1cm} (5.17)
In further considerations, the correction term is taken to be \( f_r = 0.77 \) (Waclawik and Branny, 2004).

### 5.4.7 Heat flow by evaporation at the skin surface, \( E \)

The maximum evaporative heat flow at the skin surface, \( E_{\text{max}} \), is that which can be achieved in the hypothetical case of the skin being completely wetted. In these conditions:

The evaporative resistivity of the layer separating the clothing and the air is calculated as:

\[
R_e = \frac{1}{16.7 h_c f_{cll}}
\]  
(5.18)

\[
E_{\text{max}} = \frac{(P_{sk} - P_a)}{R_e} \quad \text{W/m}^2
\]  
(5.19)

In the case of a partially wetted skin, the evaporation heat flow, \( E \), in watts per square meter, is given by (Gagge, 1981):

\[
E = \omega E_{\text{max}} \quad \text{W/m}^2
\]  
(5.20)

\( E \) is the evaporative heat transfer rate and \( \omega \) is the skin wettedness.

\[
E = \omega h_e f_{ec} (P_{sk} - P_a) \quad \text{W/m}^2
\]  
(5.21)

\( P_{sk}, P_a = \) saturation partial vapor pressure at the skin temperature and in the ambient air, respectively, \( f_{ec} = \) clothing permeability factor for vapor transfer and \( h_e = \) Latent heat transfer coefficient, W/(m\(^2\) Pa).

The coefficient of evaporative heat transfer is related to the convection heat exchange coefficient \( h_c \):

\[
h_e = 16.5 \times 10^{-3} h_c \quad \text{W/ (m}^2\text{Pa)}
\]  
(5.22)

The effective clothing permeability for vapor transfer is expressed as:
The required skin wettedness is expressed as follows and it falls in the range $0 \leq \omega_{\text{req}} \leq 1$

$$\omega = \frac{E}{E_{\text{max}}} = \frac{M-(C+R+B)}{h_{\text{eff}}(P_{sk}-P_0)}$$

(5.24)

The coefficient of heat transfer by convection is expressed as:

$$h_c = 8.7v_{ar}^{0.5} \quad \text{When } v_{ar} > 1 \text{ m/s}$$

(5.25)

$v_{ar}$ = relative velocity of airflow, m/s.

For humans engaged in hard physical work, the relative velocity $v_{ar}$ equals:

$$v_{ar} = v + 5.2 \times 10^{-3}(M - 58), \text{ m/s}$$

(5.26)

### 5.4.8 Heat storage, S

The heat storage of the body is given by the algebraic sum of the heat flows defined previously. For steady states, this is often taken as zero to assure comfort in the human body.

### 5.5 Calculation of ISO 7933 Indices

With regards to the hypotheses made concerning the heat transfer by conduction, mechanical power, and heat storage, the general heat balance Equation (5.2) can be written as:

$$M - (C + R + B + E + K + W) = 0, \quad W/m^2$$

(5.27)

$$M = C + R + B + E, \quad W/m^2$$

(5.28)
The required evaporative heat flow, $E_{req}$, is the evaporation heat flow required for the maintenance of the thermal equilibrium of the miners’ body and, therefore, for the heat storage to be equal to zero. It is defined as the difference between the metabolic rate and the sum of convective and radiation heat transfer and is given by: Respiratory heat exchange is often ignored (Waclawik and Branny, 2004).

$$E_{req} = M - (C + R) \quad (5.29)$$

The required skin wettedness, $\omega_{req}$ is the ratio between the required evaporative heat transfer and the maximum evaporative heat flow at the skin surface:

$$\omega_{req} = \frac{E_{req}}{E_{max}} = \frac{M-(C+R+B)}{h_{efec}(P_{sk}-P_a)} \quad (5.30)$$

The maximum wettedness is 1 for acclimatized workers and 0.85 for non-acclimatized workers.

The calculation of the required sweat rate is made on the basis of the required evaporative heat flow, but taking into account of the fraction of sweat that trickles away because of the large variations in local skin wettedness. The required sweat rate is given by:

$$SW_{req} = \frac{E}{\eta} \quad (5.31)$$

$\eta$ is the sweat evaporation efficiency and is dimensionless. Under very humid conditions it is given by the relationship:

$$\eta = 1 - \frac{\omega^2}{2} \quad (5.32)$$

The rate of sweat production in g/(hm$^2$) can be expressed in W/m$^2$, multiplying
The maximum sweat rate (in g/h) is a function of the metabolic rate (M in watts) according to:

\[ SW_{max} = 2.62M - 148 \quad \text{(Unacclimatized worker)} \]  
\[ SW_{max} = 3.27M - 186 \quad \text{(Acclimatized worker)} \]  

The TLV of allowable exposure time \( T_{max} \) is calculated based on the maximum tolerable dehydration \( D_{max} \) for one working day. The limit on duration of exposure is computed for an average subject on the basis of a maximum water loss (dehydration) of 7.5% of the body mass, and has to be reduced by 33% in order to protect 95% of the miner population (Malchaire, 2000).

\[ T_{max} = \frac{D_{max}}{SW} \text{ (Hrs.)} \]  

Figures (1) through (70) in the appendix presents a detail sequence of the simulation results for the required sweat production rate (SW), the skin wettedness (\( \omega \)) and the TLV of allowable exposure time (Tmax).

### 5.6 Summary

This chapter analyzed the interaction between the human body and its environment. The human body is fundamentally a constant-temperature device. Heat is continuously produced by bodily processes and dissipated in an automatically regulated manner to maintain the body temperature at its correct level despite variations in ambient conditions. In terms of physiology, the experience of comfort is the achievement of thermal equilibrium with the minimum amount of body regulation.
The human body normally rejects heat to the environment using evaporative cooling and the heat transfer mechanisms of radiation, convection, and conduction. The relative roles of these heat transfer mechanisms are determined by the individual’s metabolism, clothing, and activity level, as well as by the surrounding environmental conditions of radiation, humidity, air temperature, and air velocity. The acceptable value of each of these features is not fixed, but can vary in conjunction with one or more of the others. It is possible for the body to vary its own balance of losses, for example, through increased sweating; or the insulating value of the clothing worn can be varied to a limited degree to compensate for conditions beyond the body’s ability to make its own adequate adjustment.

The ISO indices for assessing the stressfulness of a hot industrial environment are calculated. The method is based on a comparison between the required sweat production as a result of the working conditions and the maximum physiologically achievable skin wettedness and sweat production. The standard requires calculating the sweat evaporation rate required to maintain body thermal equilibrium, calculating the maximum sweat evaporation rate permitted to the ambient environment, and calculating the sweat rate required to achieve the needed skin wettedness. The cooling efficiency of sweat as modified by the clothing worn is included in the calculation of the required skin wettedness.
CHAPTER 6: MINER THERMAL COMFORT ANALYSIS

It is prudent studying the sensitivity of environmental and physiological conditions on miner comfort so that when one of air temperature, humidity, mean radiant temperature, air velocity, metabolic rate and clothing is out of the comfort range, adjusting one or more of the other conditions will restore comfort with the addition of little or no additional energy. The sensitivity of these climate and personal factors will be tested on the ISO 7933 indices of sweat rate, skin wettedness and Maximum exposure time. Several simulations results are presented in Appendix A, Appendix B, and Appendix C in the form of figures.

6.1 Required Sweat Rate

6.1.1 Sensitivity Analysis of Air Velocity on Sweat Rate

The air velocity sensitivity analysis of sweat production rate is depicted in Table 6.1. Considering the air temperature results at 0 m/s as the benchmark, the decreasing air temperature requirements as velocity increases is computed. As air velocity increases from zero (0) to four (4), there is a corresponding increase in air temperature until a velocity of 1.5 m/s is reached. Above 1.5 m/s, the effect of air velocity on air temperature reverses and decreases as the velocity increases. This illustrates that the optimum effect of air velocity on sweat rate for comfort is achieved at 1.5 m/s after which increasing air velocity is purposely done to lower air temperatures. In Figure 6.1 and Figure 6.2, the air temperature requirement to achieve the maximum sweat rate is decreased as the air velocity increases from 1.5 m/s to 3.5 m/s.
The analysis shows that miners comfort increased with increasing air velocity and decreasing temperature as a result of achieving the necessary sweat production. Air velocity affects body heat transfer by convection and evaporation.

The air motion across the skin accomplished cooling through both convective energy transfer and latent energy transfer (evaporative of perspiration from skin). If the air temperature is less than skin temperature it will significantly increase convective heat losses. This occurs because more air is coming in contact with the warm skin as it blows past. With little or no air movement, the air close to the skin quickly heats up to the ambient skin temperature and air movement occurs only when it becomes more buoyant. So, the comfort temperature is dependent on air velocity.

In hot-humid environments (50-100 % RH), air velocity will accelerate the evaporation of sweat by moving saturated air away from the skin and replacing it with unsaturated air. Below 50% relative humidity (RH), let say at 20% RH the ventilating air is dry and the flow velocity will increase moisture removal at skin surface increasing cooling due to evaporative processes. Above 80-100 % RH, there is very little evaporative potential as the air blowing past is already close to saturation, making air movement relatively ineffective.
Figure 6.1: Sweat rate analysis as a function of air temperature and relative humidity at $M=260 \, \text{W/m}^2$, $V_a=1.5 \, \text{m/s}$.

Figure 6.2: Sweat rate analysis as a function of air temperature and relative humidity at $M=260 \, \text{W/m}^2$, $V_a=3.5 \, \text{m/s}$.
Table 6.1: Air velocity effect on air temperature requirement of sweat rate with varying humidity at metabolic rate of 200 W/m$^2$

<table>
<thead>
<tr>
<th>Relative Humidity (RH), %</th>
<th>Air Velocity (Va), m/s</th>
<th>Decreasing Temperature Requirement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>50</td>
<td>34.53</td>
<td>4.17</td>
</tr>
<tr>
<td>60</td>
<td>32.82</td>
<td>4.20</td>
</tr>
<tr>
<td>70</td>
<td>31.23</td>
<td>4.23</td>
</tr>
<tr>
<td>80</td>
<td>29.74</td>
<td>4.20</td>
</tr>
<tr>
<td>90</td>
<td>28.31</td>
<td>4.20</td>
</tr>
<tr>
<td>100</td>
<td>26.93</td>
<td>4.20</td>
</tr>
</tbody>
</table>

6.1.2 Sensitivity Analysis of Relative Humidity on Sweat Rate

Figure 6.3 and Table 6.2 presents the sensitivity analysis of humidity on required sweat rate. With relative humidity at 50 % being the benchmark (highlighted yellow row), the corresponding decrease in air temperature requirement is calculated. From Table 6.2, it is seen that increasing the air velocity will not improve air temperature requirement as long as the humidity increases. At air velocity of 4 m/s and a saturated climate, there is the highest demand for lower temperatures. This also verified the fact that with humidity kept constant, air temperatures variations appears minor with increasing velocity. At constant velocity, however, the air temperature requirement much more significant with increasing humidity. Thus, it can be concluded based on this analysis that humidity has more impact on comfort than air velocity.

In hot humid conditions typical of an underground mine, the evaporation of sweat is suppressed. Normally, the body cools itself by opening pores on the skin and releasing water and salts. As the water evaporates, it transfers the body’s heat to the air. Because water has a high latent heat, which is the heat required to change liquid water to vapor, this
process usually carries away enough heat to do a good job of cooling the body. But the rate at which water or in this case, sweat evaporates depends on how much water is already in the air. On dry climates, sweat evaporates quickly, which means it also carries away heat faster. On humid climates, when the air is already saturated with water, sweat evaporates more slowly. When relative humidity reaches a high enough level, the body’s natural cooling system simply can’t work. Sweat evaporates very slowly, if at all, and the body heats up.

This heating up of the body is the reason why lower temperatures are required in humid environments to produce the necessary sweat evaporation for comfort. As observed in Figure 6.3, the effect of humidity on sweat production is only realized after the temperature reaches 24 °C. At this temperature, airflow velocity of 1.5 m/s, and 200 W/m² metabolic rate not much sweat is produced as the worker is in its comfort zone.

**Table 6.2: Relative humidity effect on air temperature requirement of sweat rate with varying humidity at metabolic rate of 200 W/m²**

<table>
<thead>
<tr>
<th>Relative Humidity (RH), %</th>
<th>Air Velocity (Va), m/s</th>
<th>Decreasing Temperature Requirement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>50</td>
<td>34.53</td>
<td>35.97</td>
</tr>
<tr>
<td>60</td>
<td>4.95</td>
<td>4.92</td>
</tr>
<tr>
<td>90</td>
<td>18.01</td>
<td>17.99</td>
</tr>
<tr>
<td>100</td>
<td>22.01</td>
<td>21.99</td>
</tr>
</tbody>
</table>
6.1.3 Sensitivity Analysis of Metabolic Rate on Sweat Rate Production

The sensitivity analysis of metabolic rate on worker’s sweat rate production is depicted in Table 6.3 below and Figure 6.2 and Figure 6.3 above. The highlighted column at 200 W/m² activity rate in Table 6.3 is taken as the benchmark; from which the air temperature requirement is calculated. In Table 6.3 as the metabolic rate increases, there is increasing demand to maintain lower air temperatures in order to achieve the sweat production necessary for comfort.

In Figure 6.3 above, at 90 % relative humidity, the maximum sweat production is achieved at an ambient air temperature of 30 °C. As the metabolic rate increases in Figure 6.2, the air temperature requirement is decreased to ~28 °C. So, with higher metabolic rates
miners are more thermally sensitive and consequently the risk of discomfort is higher. Table 6.3 through to Table 6.7 illustrates the activity rate effect on required sweat rate based on air temperature requirement with varying air velocity. The cells highlighted yellow represents the benchmarks upon which temperature requirements are calculated. The results in these tables also support the observation that increasing activity rates demand lower air temperatures to ensure comfort.

Table 6.6 and Table 6.7 again illustrates how the optimal air velocity for comfort is achieved at 1.5 m/s. Also, the results in the tables depict that the metabolic rate has much impact on comfort than air velocity.

Therefore, the greater the activity rate, the lower should be the air temperatures to ensure comfort. The human body can handle higher temperatures at lower metabolic rates. The impact of metabolic rate on thermal comfort is critical. As metabolic rates increase, the more heat we produce. The more heat we produce, the more heat needs to be lost so we don’t overheat. Sweat production and thus its evaporation becomes a more and more important factor for thermal comfort.

Table 6.3: Decreasing air temperature requirement as a result of increasing metabolic rate and humidity at constant air velocity of 1.5 m/s.

<table>
<thead>
<tr>
<th>Metabolic Activity (W/m²)</th>
<th>Air Temperature (°C)</th>
<th>Decreasing Temperature Requirement (%)</th>
<th>Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>220</td>
<td>240</td>
<td>260</td>
</tr>
<tr>
<td>36.50</td>
<td>1.37</td>
<td>2.74</td>
<td>4.38</td>
</tr>
<tr>
<td>34.80</td>
<td>1.72</td>
<td>3.45</td>
<td>5.46</td>
</tr>
<tr>
<td>33.10</td>
<td>1.81</td>
<td>3.93</td>
<td>5.74</td>
</tr>
<tr>
<td>31.50</td>
<td>1.90</td>
<td>4.13</td>
<td>6.03</td>
</tr>
<tr>
<td>30.00</td>
<td>2.33</td>
<td>4.33</td>
<td>6.67</td>
</tr>
<tr>
<td>28.50</td>
<td>2.46</td>
<td>4.56</td>
<td>7.02</td>
</tr>
</tbody>
</table>
Table 6.4: Simulated results of air temperature as a percentage at air flow velocities in the range 0-4 m/s at RH = 50 %

<table>
<thead>
<tr>
<th>RH = 50 %</th>
<th>Air Velocity (Va), m/s</th>
<th>Decreasing Ambient Temperature Requirements at the Face (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>Metabolic Rate W/m(^2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>34.53</td>
<td>35.97</td>
</tr>
<tr>
<td>220</td>
<td>1.22</td>
<td>1.42</td>
</tr>
<tr>
<td>240</td>
<td>2.61</td>
<td>3.00</td>
</tr>
<tr>
<td>260</td>
<td>4.17</td>
<td>4.70</td>
</tr>
<tr>
<td>300</td>
<td>7.67</td>
<td>8.37</td>
</tr>
<tr>
<td>320</td>
<td>9.59</td>
<td>10.34</td>
</tr>
<tr>
<td>340</td>
<td>11.58</td>
<td>12.37</td>
</tr>
</tbody>
</table>

Table 6.5: Simulated results of air temperature as a percentage at constant air flow velocities in the range of 0-4 m/s at RH = 70 %

<table>
<thead>
<tr>
<th>RH = 70 %</th>
<th>Air Velocity (Va), m/s</th>
<th>Decreasing Ambient Temperature Requirements at the Face (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>Metabolic Rate W/m(^2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>31.23</td>
<td>32.55</td>
</tr>
<tr>
<td>220</td>
<td>1.63</td>
<td>1.87</td>
</tr>
<tr>
<td>240</td>
<td>3.39</td>
<td>3.81</td>
</tr>
<tr>
<td>260</td>
<td>5.28</td>
<td>5.84</td>
</tr>
<tr>
<td>280</td>
<td>7.27</td>
<td>7.90</td>
</tr>
<tr>
<td>320</td>
<td>11.50</td>
<td>12.23</td>
</tr>
</tbody>
</table>
Table 6.6: Simulated results of air temperature at constant activity rates in the range 200-340 W/m² at RH = 50 %

<table>
<thead>
<tr>
<th>Metabolic Rate W/m²</th>
<th>0</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
<th>3.5</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>34.53</td>
<td>4.17</td>
<td>5.50</td>
<td>5.82</td>
<td>5.56</td>
<td>5.01</td>
<td>4.26</td>
<td>3.36</td>
<td>2.37</td>
</tr>
<tr>
<td>220</td>
<td>34.11</td>
<td>3.96</td>
<td>5.31</td>
<td>5.63</td>
<td>5.42</td>
<td>4.90</td>
<td>4.16</td>
<td>3.28</td>
<td>2.29</td>
</tr>
<tr>
<td>240</td>
<td>33.63</td>
<td>3.75</td>
<td>5.11</td>
<td>5.47</td>
<td>5.29</td>
<td>4.79</td>
<td>4.04</td>
<td>3.18</td>
<td>2.17</td>
</tr>
<tr>
<td>260</td>
<td>33.09</td>
<td>3.60</td>
<td>4.99</td>
<td>5.38</td>
<td>5.20</td>
<td>4.71</td>
<td>3.96</td>
<td>3.08</td>
<td>2.09</td>
</tr>
<tr>
<td>280</td>
<td>32.51</td>
<td>3.45</td>
<td>4.86</td>
<td>5.26</td>
<td>5.11</td>
<td>4.61</td>
<td>3.88</td>
<td>2.98</td>
<td>1.97</td>
</tr>
<tr>
<td>300</td>
<td>31.88</td>
<td>3.39</td>
<td>4.77</td>
<td>5.21</td>
<td>5.08</td>
<td>4.58</td>
<td>3.86</td>
<td>2.95</td>
<td>1.91</td>
</tr>
<tr>
<td>320</td>
<td>31.22</td>
<td>3.30</td>
<td>4.71</td>
<td>5.16</td>
<td>5.03</td>
<td>4.55</td>
<td>3.81</td>
<td>2.88</td>
<td>1.83</td>
</tr>
<tr>
<td>340</td>
<td>30.53</td>
<td>3.24</td>
<td>4.65</td>
<td>5.11</td>
<td>5.01</td>
<td>4.52</td>
<td>3.77</td>
<td>2.82</td>
<td>1.74</td>
</tr>
</tbody>
</table>

Table 6.7: Simulated results of air temperature at constant activity rates in the range 200-340 W/m² at RH = 70 %

<table>
<thead>
<tr>
<th>Metabolic Rate W/m²</th>
<th>0</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
<th>3.5</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>31.23</td>
<td>4.23</td>
<td>5.60</td>
<td>5.89</td>
<td>5.67</td>
<td>5.09</td>
<td>4.35</td>
<td>3.43</td>
<td>2.43</td>
</tr>
<tr>
<td>220</td>
<td>30.72</td>
<td>3.97</td>
<td>5.37</td>
<td>5.70</td>
<td>5.47</td>
<td>4.92</td>
<td>4.17</td>
<td>3.26</td>
<td>2.25</td>
</tr>
<tr>
<td>240</td>
<td>30.17</td>
<td>3.78</td>
<td>5.17</td>
<td>5.54</td>
<td>5.34</td>
<td>4.71</td>
<td>4.04</td>
<td>3.12</td>
<td>2.06</td>
</tr>
<tr>
<td>260</td>
<td>29.58</td>
<td>3.62</td>
<td>5.04</td>
<td>5.41</td>
<td>5.24</td>
<td>4.70</td>
<td>3.96</td>
<td>3.01</td>
<td>1.96</td>
</tr>
<tr>
<td>280</td>
<td>28.96</td>
<td>3.52</td>
<td>4.94</td>
<td>5.32</td>
<td>5.18</td>
<td>4.63</td>
<td>3.87</td>
<td>2.94</td>
<td>1.86</td>
</tr>
<tr>
<td>300</td>
<td>28.32</td>
<td>3.43</td>
<td>4.84</td>
<td>5.26</td>
<td>5.08</td>
<td>4.59</td>
<td>3.81</td>
<td>2.86</td>
<td>1.77</td>
</tr>
<tr>
<td>320</td>
<td>27.64</td>
<td>3.36</td>
<td>4.81</td>
<td>5.25</td>
<td>5.10</td>
<td>4.59</td>
<td>3.80</td>
<td>2.82</td>
<td>1.74</td>
</tr>
<tr>
<td>340</td>
<td>26.95</td>
<td>3.30</td>
<td>4.75</td>
<td>5.23</td>
<td>5.08</td>
<td>4.56</td>
<td>3.71</td>
<td>2.78</td>
<td>1.63</td>
</tr>
</tbody>
</table>

The metabolic rate depends on the activity and the fitness level. At lower air temperatures i.e. temperatures less than the skin temperature (36 °C), convective heat loss
increases with decreasing humidity, thereby decreasing the heat load on the human body and resulting in a wider range of activity before discomfort is felt. The maximum range of activity in which people feel comfortable is therefore achieved by minimizing air temperature and humidity while compensating with an activity rate sufficient to maintain comfort.

6.1.4 Required sweat production as an index of thermal strain

In order to satisfy the requirement for an index to assess thermal strain, an index should incorporate into its birth the six influencing factors: metabolic heat expenditure, clothing, air and mean radiant temperature, humidity and air velocity; the index shall allow the evaluation of the degree of discomfort as well as safe exposure times; and that the measure and calculation shall be simple and rapid (Vogt et. al. 1981). Since this index was derived from the heat balance equation, it is directly proportional to the physiological strain. The larger the index the larger the strain. Required sweat production corresponds to the maximum sweat that must be realized to match the thermal stress.

Upper tolerable values of required sweat rate are proposed by (ISO 7933, 2004). These limit criteria are based on the maximum sweat rate. The maximum sweat rate depends on the acclimatization of the miner to his environment. Acclimatized miners will sweat more, uniformly on their body surface, earlier than non-acclimatized and losses less salt. Non-acclimatized workers are limited to a sweat requirement of 650 g/h to 1000 g/h. Acclimatized workers can sweat more. As high as 2500 g/h is reported in some instances. For this studies 1000 g/h to 1300 g/h is considered as the threshold (Vogt et. al. 1981). The
maximum sweat rate is a function of the metabolic rate. Climate conditions with required sweat rate below these threshold values will be considered safe for the miner.

Figure 6.4: Required sweat rate simulated results in the working face at 200 W/m² and air velocity of 1.5 m/s.

Figure 6.4 shows simulated results of required sweat rate in a range between 175 g/h and 850 g/h. These values are below the proposed upper limit values and so the condition of the working face are safe for the miners.
6.2 Skin Wettedness

6.2.1 Sensitivity Analysis of Air Velocity on Skin Wettedness

The percentage of skin wettedness is altered by the air velocity which is a function of the evaporative heat coefficient, expressed as \( h_e = 16.5 \times 10^{-3} h_c \), where \( h_c \) is the convective heat transfer coefficient and is dependent on air velocity \( (h_c = 8.7v^{0.5}) \). Just like in the sweat rate, the optimum air velocity effect on skin wettedness occurred at 1.5 m/s. Above that, the velocity seems to play the part of reducing air temperature. This is illustrated in Table 6.8 and Figure 6.5.

Table 6.8: Air velocity effect on air temperature requirement of skin wettedness with varying Humidity at a metabolic rate of 200 W/m².

<table>
<thead>
<tr>
<th>M=200 W/m²</th>
<th>0</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
<th>3.5</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Humidity (RH), %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>37.27</td>
<td>38.95</td>
<td>39.52</td>
<td>39.66</td>
<td>39.60</td>
<td>39.41</td>
<td>39.16</td>
<td>38.85</td>
<td>38.50</td>
</tr>
<tr>
<td>60</td>
<td>34.67</td>
<td>36.21</td>
<td>36.72</td>
<td>36.83</td>
<td>36.77</td>
<td>36.59</td>
<td>36.34</td>
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<td>70</td>
<td>32.46</td>
<td>33.89</td>
<td>34.36</td>
<td>34.46</td>
<td>34.38</td>
<td>34.20</td>
<td>33.96</td>
<td>33.66</td>
<td>33.34</td>
</tr>
<tr>
<td>80</td>
<td>30.51</td>
<td>31.85</td>
<td>32.28</td>
<td>32.37</td>
<td>32.29</td>
<td>32.11</td>
<td>31.87</td>
<td>31.58</td>
<td>31.26</td>
</tr>
<tr>
<td>90</td>
<td>28.73</td>
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<td>30.40</td>
<td>30.47</td>
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<tr>
<td>100</td>
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<td>28.28</td>
<td>28.66</td>
<td>28.73</td>
<td>28.64</td>
<td>28.46</td>
<td>28.23</td>
<td>27.95</td>
<td>27.65</td>
</tr>
</tbody>
</table>
6.2.2 Sensitivity Analysis of Relative Humidity on Skin Wettedness

The changes of skin wettedness on humidity are given in Figure 6.6 and Figure 6.7 for air velocity of 1.5 m/s and metabolic rate of 200 W/m$^2$ and 260 W/m$^2$ respectively. It is observed that for air temperatures between 28.7 °C and 39.7 °C in Figure 6.6 and temperatures between 26.6 °C and 37.4 °C in Figure 6.7, the relative humidity effect on skin wettedness is more effective than that of the low air temperatures. With increasing relative humidity, significant changes occur in the skin wettedness between these air temperatures. Also, maximum skin wettedness is reached at between these temperatures.
Figure 6.6: Skin wettedness analysis as a function of air temperature and relative humidity at $M=200 \text{ W/m}^2$, $V_a = 1.5 \text{ m/s}$.

Figure 6.7: Skin wettedness analysis as a function of air temperature and relative humidity at $M=260 \text{ W/m}^2$, $V_a = 1.5 \text{ m/s}$.
6.2.3 Sensitivity Analysis of Metabolic Rate on Skin Wettedness

The metabolic effect in the skin wettedness is depicted in the lower air temperature requirement observed in Figure 6.8 and Table 6.9. The generation of more heat as a result of higher activity rate requires lower air temperatures to effect heat rejection in the form of sweating. This is achieved by convective heat transfer from the heated skin in the low air temperature passing.

The analysis indicates that increasing metabolic rates demand lower air temperatures to maintain comfort for the miners.

**Table 6.9: Decreasing air temperature requirement as a result of increasing metabolic rate and humidity at an air velocity of 1.5 m/s.**

<table>
<thead>
<tr>
<th>Metabolic Activity (W/m²)</th>
<th>Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temperature</td>
<td>Decreasing Temperature Requirement (%)</td>
</tr>
<tr>
<td>200</td>
<td>220 240 260 280 300 320 340</td>
</tr>
<tr>
<td>36.50</td>
<td>1.87 3.81 5.75 7.79 9.96 11.90 14.07</td>
</tr>
<tr>
<td>34.80</td>
<td>1.95 3.96 6.03 8.12 10.26 12.44 14.69</td>
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<td>33.10</td>
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<td>2.16 4.36 6.61 8.87 11.21 13.59 16.03</td>
</tr>
<tr>
<td>30.00</td>
<td>2.26 4.56 6.92 9.28 11.75 14.24 16.80</td>
</tr>
<tr>
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<td>2.44 4.80 7.27 9.75 12.32 14.93 17.61</td>
</tr>
<tr>
<td>28.00</td>
<td>2.61 5.20 7.82 10.59 13.56 16.78 19.42</td>
</tr>
</tbody>
</table>
6.2.4 Required Skin Wettedness as an index of thermal strain

The ISO 7933 heat-stress indices are based on the concept that in addition to the sweat production required for temperature equilibrium ($E_{\text{req}}$) and the maximum amount of sweat that can be evaporated ($E_{\text{max}}$); the efficiency of sweat evaporation will also affect heat strain. The less efficient the evaporation, the greater will be the body surface area that has to be wetted with sweat to maintain the required evaporative heat transfer (Figure 6.9). In healthy, fully heat acclimatized individuals, maximum skin wettedness is considered to be 1.0, whereas this value is considered to be closer to ~0.85 in non-heat acclimatized individuals.
Figure 6.9: Relationship between sweating efficiency and skin wettedness.

Figure 6.10: Simulated results of required skin wettedness for comfort at activity rate of 300 W/m² and air velocity of 1.5 m/s.
Figure 6.10 shows the required skin wettedness of acclimatized subject at (1) and unacclimatized at (0.85). The activity is at a rate of 300 W/m² at air velocity of 1.5 m/s. If the climate is saturated i.e. 100% humidity, air temperatures should be at about 24 °C to fully protect the mine workers.

### 6.3 Maximum Worker Exposure Time Analysis Based on Comfort Parameters

A detailed analysis of the maximum exposure time to heat in the mining environment based on the comfort parameters are presented in the form of graphs in the appendix.

Upper tolerable limits of maximum sweat loss or dehydration must also be set. Dehydration will occur when the climatic conditions are such that drinking during the period of exposure cannot replenish the amount of water lost (Leithhead and Lind, 1964). ISO 7933 recommends a tolerable dehydration limit of ranging from 3.5 % to 7.5 % of the body weight (75 kg) of an average miner. In this analysis, an amount of 3900 g (5.2 %) is assumed as the upper limit of dehydration for a work shift of 8 hrs.

Harsh environmental conditions demand that a safe exposure time limit is set. The safe exposure time correlates to the maximum dehydration that can be tolerated under the defined comfort conditions.

In Figure 6.11, as long as the air temperature stays at 35 °C, the activity level in the environment should not exceed 300 W/m² for the 8 hour shift per day. In other words, the safe working time is shorter than 8 hours for metabolic rates greater than 300 W/m². Figure
6.11 also shows that at a certain temperature, the safe working time decreases as the activity rate increases.

![Graph showing safe working time vs temperature for different activity rates.

Figure 6.11: Simulated results of safe working time for comfort.

### 6.4 Analysis and Interpretation of a Given Mine Working Climate Situation

This analysis takes into consideration limit criteria recommended by ISO 7933 (1989 & 2004). The limits and results are presented in Table 6.10 and Table 6.11. Figure 6.12 through to Figure 6.14 present the evaluations at 80 % humidity from which the results were extracted. The same evaluations were done for the 50 % humidity. The reasoning is that the predicted values of the required sweat rate, skin wettedness and safe duration of exposure to heat must not exceed these limits to keep the human body in equilibrium with the stress from the environment. All conditions are the same in both climates, except the
humidity which is 80% in the first scenario and 50% in the second. The climate conditions are: $R_c = 0.093$, $M = 260$, $V_a = 1.5$, $T_a = 20-40$, RH = 80% and 50%, and $T_a = T_r$. The optimal air temperatures to achieve equilibrium are listed in the tables.

For the working faces of underground mines that are hot and humid, the air humidity sometimes can be close to saturation. Based on this premise, analysis in Table 6.11 presents a typical mining scenario.

Table 6.10: Predicted optimal air temperatures and sweat rate compared with ISO limits to meet miner body equilibrium conditions at RH = 80%

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Predicted Comfort Air Temperature ($^\circ$C)</th>
<th>ISO 2004 Limits</th>
<th>ISO 1989 Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Predicted Maximum</td>
<td>Unaccli</td>
<td>Acccli</td>
</tr>
<tr>
<td>Required Sweat Rate (SWreq), g/h</td>
<td>1134</td>
<td>28.72</td>
<td>29.55</td>
</tr>
<tr>
<td>Skin wettedness (w)</td>
<td>28.44</td>
<td>30.23</td>
<td>0.85</td>
</tr>
<tr>
<td>Permissible Exposure Time (hrs)</td>
<td>8</td>
<td>33.25</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 6.11: Predicted optimal air temperatures and sweat rate compared with ISO limits to meet miner body equilibrium conditions at RH = 50%

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Predicted Comfort Air Temperature ($^\circ$C)</th>
<th>ISO 2004 Limits</th>
<th>ISO 1989 Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Predicted Maximum</td>
<td>Unaccli</td>
<td>Acccli</td>
</tr>
<tr>
<td>Required Sweat Rate (SWreq), g/h</td>
<td>1134</td>
<td>33.38</td>
<td>34.89</td>
</tr>
<tr>
<td>Skin wettedness (w)</td>
<td>35.07</td>
<td>37.37</td>
<td>0.85</td>
</tr>
<tr>
<td>Permissible Exposure Time (hrs)</td>
<td>8</td>
<td>41</td>
<td>8</td>
</tr>
</tbody>
</table>

*Accli: Acclimatized, Unaccli: Unacclimatized
Figure 6.12: Skin wettedness for acclimatized and unacclimatized miners and optimal air temperature at 80% humidity and 260 W/m² activity rate.

Figure 6.13: Required sweat rate for acclimatized and unacclimatized miners and optimal air temperature at 80% humidity and 260 W/m² activity rate.
Figure 6.14: Allowable exposure time and optimal air temperature at 80% humidity

6.5 Summary

This chapter analyzed the sensitivity of changing the comfort parameters on the ISO 7933 indices of sweat rate, skin wettedness and maximum exposure time for thermal comfort. The analysis was done based on simulated results that have its engine as the heat balance equation. The ISO limit criteria were also employed in assessing the indices for use in evaluating thermal comfort. The study results can be usefully summarized into the following findings:

- The analysis confirms that thermal comfort is dependent on variations of climatic parameters and the miners’ personal activity levels.

- The optimal safe air temperature ranges are dependent on the thermal comfort
parameters.

- When the metabolic rate increases, internal heat generation is increased, which requires lower air temperatures to accelerate convective heat rejection.

- When the air motion across the skin increases, thermal comfort will increase and that the optimum air velocity for comfort is 1.5 m/s.

- When the humidity increases, thermal comfort is restricted as a result of suppressed sweat evaporation.

- The analysis also observed that humidity contributes a lot more to deviations from comfort. It is followed by activity level and then airflow velocity. Note that, in this study, clo is kept constant, and $T_a$ is equated to $T_r$. 
CHAPTER 7: CONCLUSIONS

7.1 Summary

The combination of environmental conditions and workloads encountered by underground miners may result in unacceptable physical stress and strain. The safety and health condition of miners and not the production targets must be the limiting factor when planning operations in thermally stressful environments.

The physical condition of miners should be monitored during operations to identify and exclude those members with an abnormal sensitivity to heat so that they do not become a risk to themselves and the entire operations.

This study analyzed the effect of changing humidity, air velocity, and metabolic rate along with air temperature on the thermal comfort of miners. Two key techniques were used in this thesis to authenticate the research. The first technique was based upon the thermodynamic analysis of the human heat balance. A detailed analysis of the various heat exchanges between the environment and the human body was carried out and quantified into a mathematical model for comfort analysis. The thermal comfort was then analyzed using the ISO 7933 required sweat rate, skin wettedness and maximum safe exposure time indices. The second technique included the use of the two stress criteria of maximum skin wettedness and maximum sweat rate and the strain criteria of maximum dehydration. The required sweat rate cannot exceed the maximum sweat rate attainable by the subject. The required skin wettedness cannot exceed the maximum skin wettedness attainable by the subject. These two conditions are dependent on the level of acclimatization of the subject to the work environment. Finally, whatever the thermal balance, the dehydration level must
be limited to a maximum value desirable to maintain the hydro-mineral equilibrium of the body. The study results can be usefully summarized into the following points:

- Maximum thermal satisfaction is attainable with higher air velocities than those that can be obtained at the lower airflow velocity.
- This study analyses and summarizes the thermal stress evaluation indices of ISO 7933 from simulations performed on the mathematical model.
- From the simulated results based on the thermal parameters of the environment, upper working limits of air temperature, activity, humidity, and air velocity can be determined and recommended.
- Maximum exposure times to minimize strain due to dehydration can also be predicted. The study also makes it possible to manipulate the environmental parameters to obtain desirable maximum exposure times value.
- The limits can be verified by simulation results of heat balance model in conjunction with the maximum criteria of required sweat rate, skin wettedness and the upper limit of working time.
- Optimum air temperatures for thermal comfort are achieved at air velocities of 1.5 m/s. When the air motion across the skin increases, thermal comfort will increase and that the optimum air velocity for comfort is 1.5 m/s.
- The analysis also observed that humidity contributes a lot more to deviations from comfort. It is followed by activity level and then airflow velocity. Note that in this study values for clothing (clo) are kept constant, and Ta is equated to Tr.
- Results from this research work was used by a graduate student to assess and determine a heat stress index that will protect U/G workers in hot mines.
7.2 Contribution

The main contributions of this study are as follows:

- Proving that the optimum air velocity requirement for thermal comfort is 1.5 m/s. This is from the simulated results of air velocity and air temperature.
- Development of a mathematical model that describes the miner comfort states based on required sweat rate, skin wettedness, and safe permissible exposure times.
- Analysis of the mathematical model sensitivity to personal and environmental conditions.
- Prediction of air temperature requirement based on the comfort parameters.
- Methods to assess accurately the risk of heat disorders encountered while working in hot and humid mines.
- These results will ensure a reduction in the cost of accidents as well as the cost of medical care due to morbidity contracted at the workplace.
- This study will help ventilation planners to control actively and effectively the maximum permissible heat exposure threshold.
- The sustainability impact of this work is to guarantee better working conditions and prevention of injuries that result from the exposure to heat.
- The results in this study was used by Mr. Pedram Roghanchi to analyze heat stress indices.
7.3 Future Work

In this study, the clo value is assumed constant at 0.6 and the radiation is assumed to be equal to the air temperature. Following the work described in this thesis, a number of projects could be taken up involving the miner comfort:

- If necessary, the stress and strain analysis can be done based on the difference between radiation and air temperature (Tr-Ta) in mine climates where the effect of radiation cannot be ignored.
- A study into the required insulation for thermal comfort for miners can also be modeled to ensure proper clothing design for miners.
CHAPTER 8: References


Blankenbaker, J. (1982). Heating/Piping/Air Conditioning. 54(60).


Organized by DEEDI Mines and the Health Improvement and Awareness Committee (HIAC), Department of Natural Resources and Mines. South Brisbane.


Du Bois, D. (1916). A Formula to Estimate Approximate Surface Area, if Height and Weight are known. *Archives of internal Medicine, 17.*


McNall, P. E.; et, al. (1967). *Thermal comfort (thermally neutral) conditions for three levels of activity* (Vol. 73). ASHRAE Transactions.


Appendix A

Assessment of sweat rate as a function of air temperature ($T_a$), humidity (RH), air velocity ($V_a$) and Metabolic rate ($M$)

(1)
(6) Comfort Iterations of required sweat rate @ M=200, Va=2.5 m/s

(7) Comfort Iterations of required sweat rate @ M=200, Va=3 m/s
Comfort Iterations of required sweat rate @ M=200, V_a=3.5 m/s

Sweat rate, g/h

Temperature, °C

Comfort Iterations of required sweat rate @ M=200, V_a=4 m/s

Sweat rate, g/h

Temperature, °C
Comfort Iterations of required sweat rate @ M=220, \( V_a=3 \text{ m/s} \)

Sweat rate, g/h vs Temperature, °C

- RH=50% (solid line)
- RH=60% (dashed line)
- RH=70% (dash-dotted line)
- RH=80% (dotted line)
- RH=90% (bold line)
- RH=100% (dashed-dotted line)
Comfort Iterations of required sweat rate @ M=280, Va=3 m/s

Sweat rate, g/h

Temperature, °C

RH=50%
RH=60%
RH=70%
RH=80%
RH=90%
RH=100%

Comfort Iterations of required sweat rate @ M=280, Va=3.5 m/s

Sweat rate, g/h

Temperature, °C

RH=50%
RH=60%
RH=70%
RH=80%
RH=90%
RH=100%
Comfort iterations of required sweat rate @ M=280, Va=4 m/s

Comfort iterations of required sweat rate @ M=300, Va=0 m/s
Comfort Iterations of required sweat rate @ M=300, Va=0 m/s

Sweat rate, g/h

Temperature, °C

RH=50%
RH=60%
RH=70%
RH=80%
RH=90%
RH=100%

Comfort Iterations of required sweat rate @ M=300, Va=0.5 m/s

Sweat rate, g/h

Temperature, °C

RH=50%
RH=60%
RH=70%
RH=80%
RH=90%
RH=100%
Comfort iterations of required sweat rate @ M=300, V_a=1 m/s

Sweat rate, g/h

Temperature, °C

RH=50%
RH=60%
RH=70%
RH=80%
RH=90%
RH=100%

Comfort iterations of required sweat rate @ M=300, V_a=1.5 m/s

Sweat rate, g/h

Temperature, °C

RH=50%
RH=60%
RH=70%
RH=80%
RH=90%
RH=100%
Comfort Iterations of required sweat rate @ $M=320$, $V_a=0$ m/s

- RH=50%
- RH=60%
- RH=70%
- RH=80%
- RH=90%
- RH=100%

Sweat rate, g/h vs Temperature, °C

Comfort Iterations of required sweat rate @ $M=320$, $V_a=0.5$ m/s

- RH=50%
- RH=60%
- RH=70%
- RH=80%
- RH=90%
- RH=100%

Sweat rate, g/h vs Temperature, °C
Comfort Iterations of required sweat rate @ M=320, Va=1 m/s

Sweat rate, g/h

Temperature, °C

RH=50%
RH=60%
RH=70%
RH=80%
RH=90%
RH=100%

Comfort Iterations of required sweat rate @ M=320, Va=1.5 m/s

Sweat rate, g/h

Temperature, °C

RH=50%
RH=60%
RH=70%
RH=80%
RH=90%
RH=100%
Comfort Iterations of required sweat rate @ $M=320, V_a=2$ m/s

(58)

Comfort Iterations of required sweat rate @ $M=320, V_a=2.5$ m/s

(59)
Comfort Iterations of required sweat rate @ M=320, Va=3 m/s

Comfort Iterations of required sweat rate @ M=320, Va=3.5 m/s
Comfort iterations of required sweat rate @ $M=340$, $Va=2$ m/s

![Graph](Image)

Comfort iterations of required sweat rate @ $M=340$, $Va=2.5$ m/s

![Graph](Image)
(70)

Comfort iterations of required sweat rate @ $M=340$, $V_a=4$ m/s

Temperature, °C

Sweat rate, g/h

- RH=50%
- RH=60%
- RH=70%
- RH=80%
- RH=90%
- RH=100%

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Appendix B

Assessment of skin wettedness as a function of air temperature (Ta), humidity (RH), air velocity (Va) and Metabolic rate (M)

(1)

![Comfort Iterations of Skin wettedness @ M=200, Va= 0 m/s](image-url)
(4) Comfort iterations of Skin wetness @ \( M=200, \ Va=1.5 \ m/s \)

(5) Comfort iterations of Skin wetness @ \( M=200, \ Va=2 \ m/s \)
Appendix C

Assessment of maximum duration of exposure time as a function of air temperature (Ta), humidity (RH), air velocity (Va) and Metabolic rate (M).

(1)
Comfort Iterations of TLV exposure time @ M=220, Va=1.5 m/s

(2)

(3)
(4) Comfort Iterations of TLV exposure time @ M=260, Va=1.5 m/s

(5) Comfort Iterations of TLV exposure time @ M=280, Va=1.5 m/s
Comfort iterations of TLV exposure time @ M=300, Va=1.5 m/s

(6)

Comfort iterations of TLV exposure time @ M=320, Va=1.5 m/s

(7)
Comfort iterations of TLV exposure time @ M=340, Va=1.5 m/s
Appendix D

MatLab code for predicting sweat rate, skin wettedness, and duration of worker exposure time

clc
clear all
i=1;
M=260; % M = Metabolic rate
I=0;
J=0;

for Ta=25:.001:50;
    RH=1; % RH = Relative humidity
    Tw=Ta* atan ((0.151977* ((RH*100) +8.313659) ^0.5)) + atan (Ta+ (RH*100))-
        atan ((RH*100)-1.676331) +0.00391838*((RH*100) ^ (3/2))*atan
        (0.023101*(RH*100))-4.686035; % Tw = Wet bulb temperature
    Va = 1; % Va = Air velocity
    Tr = Ta; % Tr = Radiation temperature
    Pr = 100000; % Pr = Atmospheric pressure
    Rcl = 0.093; % Rcl = Clothing resistance factor
    Dmax = 3900; % Dmax = Maximum dehydration capacity of a miner for per shift
    Esk = 0.97; % Esk = Coefficient of skin emissivity
    Fr = 0.77; % fr = Body area correction factor for radiation exposure
    es1 = 610.6*2.71828. ^ ((17.27.*Tw)/ (237.3+Tw)); % es1 = the saturation vapor pressure at a temperature of Tw °C
    ea = es1-(64.4*10^-5.*(Ta-Tw))*Pr; % ea = actual vapor pressure parameters of exhaled air
    Tsk = 30 + (0.138.*Ta) + (((0.254.*ea))/1000)- (0.571.* va) + (0.00128.*M)
        - (0.553.*Rcl); % Tsk = Skin temperature
    hr = 5.67.*10^-8.*4.*(((Tsk + Ta)/2)+273.15).^3;% heat transfer coefficient of radiation
\[ \text{var} = \text{va} + 0.0052 \times (\text{M} - 58) \] % var = relative velocity

\[ \text{hc} = 8.7 \times \text{var.} \times 0.6 \] % hc = heat transfer coefficient of convection

\[ \text{fc1} = 1 + 1.29 \times \text{Rc1} \] % fc1 is clothing factor

\[ \text{hrl} = \text{Fr} \times \text{Esk} \times \text{hr} \] % hrl = heat transfer coefficient of radiation correction for a standing worker

\[ \text{Ra} = \frac{1}{\text{hc} + \text{hrl}} \] % Ra = thermal insulation of the layer separating the body from the its environment

\[ \text{Rcle} = \text{Rc1} - \text{Ra} \times (1 - (1 / \text{fc1})) \] % Rcle = thermal resistance offered by clothing

\[ \text{Fcls} = (1 + (\text{hc} + \text{hrl}) \times \text{Rcle}) \times ^{-1} \] % Fcls = Transfer coefficient for sensible heat exchange

\[ \text{C} = \text{hc} \times \text{Fcls} \times (\text{Tsk} - \text{Ta}) \] % C = Convective heat transfer

\[ \text{R} = ((\text{Fr} \times \text{Esk}) \times \text{hr}) \times \text{Fcls} \times (\text{Tsk} - \text{Tr}) \] % R = Radiation heat transfer

\[ \text{Ereq} = \text{M} - (\text{C} + \text{R}) \] % Ereq = Required evaporation level Note: respiratory heat exchange is often ignored (Waclawik and Branny, 2004)

\[ \text{Psk} = 610.6 \times \exp \left( \frac{17.27 \times \text{Tsk}}{237.3 + \text{Tsk}} \right) \] % Psk = saturation vapor pressure at skin temperature

\[ \text{Fc1l} = \frac{1}{1 + 0.92 \times \text{hc} \times \text{Rcle}} \] % Fc1l = Transfer coefficient latent heat exchange

\[ \text{Re} = \frac{1}{16.7 \times 10^{-3} \times \text{hc} \times \text{Fc1l}} \] % Re = Total resistance from evaporation

\[ \text{Emax} = \text{abs} (\text{Psk} - \text{ea}) / \text{Re} \] % Emax = Maximum Evaporative heat transfer

\[ \text{W} = \text{Ereq} / \text{Emax} \] % W = skin wettedness

\[ \text{SWE} = 1 - (\text{W}^2) / 2 \] % SWE = index of sweating efficiency

\[ \text{SWreq} = \text{Ereq} / \text{SWE} \] % SWreq = is the required sweat rate

\[ \text{SWreqgh} = 1.4868 \times \text{SWreq} \times 1.9 \] % SWreqgh = is the required sweat rate in g/h

\[ \text{Tup} = \text{Dmax} / \text{SWreqgh} \] % Tup = Worker tolerable time
MaxSW = ((M*1.9)-58)*2.6; % MaxSW = maximum sweat rate (in g/h)

%MaxSW = 2.62*M-148; % maximum sweat rate (in g/h) (Unacclimatized worker)
%MaxSW = 3.27*M-186; % maximum sweat rate (in g/h) (Acclimatized worker)

if SWreqgh <= MaxSW && (I==0)
    SWrate (i) = SWreqgh;
else
    I=1;
    SWrate (i) = NaN;
end

wet (i) = w;
if w<=1
    wet (i) = w;
else
    wet (i) = NaN;
end

if Tup>=0 && J==0
    ExposureLimit (i) = Tup;
else
    J=1;
    ExposureLimit (i) = NaN;
end

i = i+1;
end

hold on

plot (ta, ExposureLimit, 'k', 'LineWidth', 1.5, 'LineStyle', '-');

% legend ('M(300), RH=50%', 'M(220)', 'M(300), V=1 m/s', 'M(300), V=1.5 m/s', 'V(300), V=2 m/s', 'V(300), V=2.5 m/s', 'V(300), V=3 m/s', 'M(300), V=3.5 m/s', 'V(300), V=4 m/s', 'Location', 'best');

Legend
('RH=50%', 'RH=60%', 'RH=70%', 'RH=80%', 'RH=90%', 'RH=100%', 'Location', 'best');

% legend ('V=0 m/s', 'V=0.5 m/s', 'V=1 m/s', 'V=1.5 m/s', 'V=2 m/s', 'V=2.5 m/s', 'V=3 m/s', 'V=3.5 m/s', 'V=4 m/s', 'Location', 'best');
% legend ('M (200)', 'M (220)', 'M (240)', 'M (260)', 'M (280)', 'M (300)', 'M (320)', 'M (340)', 'Location', 'best');

xlabel ('Temperature, °C');
ylabel ('TLV exposure time, hrs');
ax = gca;
ylim ([0, 8]);
xlim ([25, 40]);
set (ax,'yTick', [0:1:8]);
set (ax,'xTick', [0:2:40]);

grid on

Title ('Comfort Iterations of TLV exposure time @ M=200, Va = 1.5 m/s');
set(gca,'FontSize',10); set(gca,'FontName','arial');
set(gca,'FontWeight','bold'); set(gcf,'Color',[1,1,1]);