Proceedings of the
International Conference on Mechanical Engineering and Renewable Energy 2017
(ICMERE2017) 18 – 20 December, 2017, Chittagong, Bangladesh

ICMERE2017-PI-128

A THERMAL DRESS FOR HUMAN COMFORT

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Abstract*- The working environment remains very hot and humid almost throughout the year in Bangladesh. People who have to work on the extremely hot or cold conditions may feel differently. The exposure of workers to extreme heat or cold can result in thermal stresses. Thermal stress can be the source of considerable physical and psychological discomfort. Sometimes it causes serious illness and injuries, even death. A reasonable degree of bodily comfort should be the normal expectation of all men as they carry out their functions in the workplace. This paper aims to discuss health risks associated with working in extreme hot and cold situations, and to suggest reasonable solution for a dress, named thermal dress, which is compatible with the workplace. A thermal dress is a dress that can control its temperature itself in a range, irrespective of environment condition. This dress contains a cloth in which micro-tubes are sewn. A working fluid, water in this case, is flowed through these micro-tubes. A small reservoir, named hydration-backpack, contains the fluid and a small pump circulates the fluid. The temperature of the fluid in the reservoir is controlled within a range with temperature controller and thermoelectric cooling device (TEC). Thermoelectric cooling devices operate according to the Peltier effect. This dress gives a better environment for human comfort irrespective of environmental conditions. It is compatible for the people who work in hot and humid conditions, such as farmers working in the field in the hot, sunny day; workers working in the factory, specially, who work near furnace etc.*

Keywords: Thermal stresses, Health risks, Peltier effect, Thermal dress, Human comfort.

1. INTRODUCTION

The body works best when it has an internal “core” temperature of 37°C. The human body operates within a very narrow core temperature band. While there are diurnal variations, normal internal core body temperature usually ranges from 36.8°C to 37.2°C. To maintain this internal temperature balance, any heat impact on the body, whether from external environmental conditions or generated as a result of work performed by the individual, must be balanced by an equivalent heat loss from the body. If this does not occur, there is a net heat gain and heat stress is experienced by the individual.

37°C might seem warm, but this is the internal temperature (not the environment air temperature). This temperature is necessary for the vital organs to function normally. During a regular day, the body temperature may vary by about 1°C depending on the time of day, level of physical activity and how one is feeling (emotional reactions). The body’s metabolic processes produce the right amount of heat, when needed from digestion of food and when performing physical activity [1].

1.1 Objectives

Objectives of this study are –

1) To study thermal stresses on human body and their possible health risks.
2) To make a thermal dress.

2. THERMAL COMFORT DEFINITION

Thermal comfort has been defined by Hensen as “a state in which there are no driving impulses to correct the environment by the behavior” [2]. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defined it as “the condition of the mind in which satisfaction is expressed with the thermal environment” [3].

Thermal sensations are different among people even in the same environment. Even though the sensors render the same results regardless to the geographical position where a measurement is being taken, this is not the case for persons. Indeed, persons staying in very similar spaces, subjected to the same climate, and belonging to a common culture, issue very different opinions on thermal comfort due to the combination of a large number of factors that affect the perception of human beings [4]. As such, thermal comfort may be influenced by personal differences in mood, culture and other individual, organizational and social factors. Based on the above definitions, comfort is not a state condition, but rather a state of mind. The definition of thermal comfort leaves open as to what is meant by condition of mind or satisfaction, but it correctly emphasizes that the judgment of comfort is a cognitive process involving many inputs influenced by physical, physiological, psychological, and other factors [5].

Conventionally, thermal discomfort is treated as a subjective condition while thermal sensation is an objective sensation [2]. Satisfaction with the thermal environment is a complex subjective response to several interacting and less tangible variables [6]. In other words, there is really no absolute standard for thermal comfort. In general, comfort occurs when body temperatures are held within narrow ranges, skin moisture is low, and the physiological effort of regulation is minimized. Comfort also depends on behavioral actions such as altering clothing, altering activity, changing posture or location, changing the thermostat setting, opening a window, complaining, or leaving a space.

3. ADAPTABILITY OF HUMAN BODY

When men work in extreme temperatures, the body has to adapt. To maintain a constant inner body temperature, the body must continually keep or gain heat in cold environments and lose heat in hot environments.

To stay warm in cold environments, the body makes some adaptions, including the following processes:

• Shivers: It is a process of moving muscles that helps increase heat production, and

• Reduces blood flow to the skin and extremities (hands and feet) to reduce heat loss from the surface.

To stay cool in hot environments, the body also makes some adaptions, including the following processes:

• Sweats: It is a process of sweating that cools the body.

• Increases blood flow to the skin – to speed up the loss of heat from the skin i.e., radiate away the excess heat, if the outside air is cooler, and

• Acclimatization: People can adapt to hotter temperatures through a process called “acclimatization.” At the workplace, acclimatization is important because it allows you to work more safely and efficiently. However, becoming acclimatized takes time.

By sweating, shivering, and changing the rate of blood flow, the body can adapt to a fairly wide range of temperatures. The most effective means of regulating temperature is via this evaporation of sweat, which may account for up to 98% of the cooling process [8]. However, there are limits to what the body can adapt to and its ability to maintain its core temperature can fail.

Figure 1 shows the temperature distribution of human body. The core temperature is always same, whatever the environment temperature. The skin temperature may vary with environment. Skin temperature falls in cold environment as low as 26°C. But in hot environment it remains at 36°C by sweating.

4. THERMAL STRESSES AND HEALTH RISKS

There are two types of thermal stresses: (i) heat stress and (ii) cold stress.

4.1 Heat Stress

Heat stress is the overall heat load on the body, including environmental heat and inner body heat production due to working hard. Mild or moderate heat stress may be uncomfortable and may affect performance and safety, but it is not usually harmful to your health.

Heat stress occurs “when a person’s environment (air temperature, radiant temperature, humidity and air velocity), clothing and activity interact to produce a tendency for body temperature to rise”.

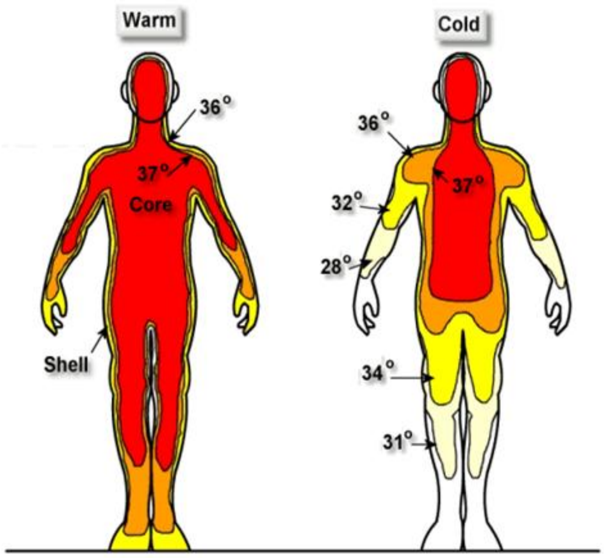

Figure 1: Temperature distribution of human body [7].

4.2 Effects of Heat Exposure

The US Center for Disease Control and Prevention explained: “Workers who are exposed to extreme heat or work in hot environments may be at risk of heat stress. Exposure to extreme heat can result in occupational illnesses and injuries. Heat stress can result in heat stroke, heat exhaustion, heat cramps, or heat rashes. Heat can also increase the risk of injuries in workers as it may result in sweaty palms, fogged-up safety glasses, and dizziness. Workers at risk of heat stress include outdoor workers and workers in hot environments such as firefighters, bakery workers, farmers, construction workers, miners, boiler room workers, factory workers, and others [8]”.

Healthy people can physically adapt to changes in ambient temperature within some limits. However, when temperatures push the upper end of those limits or are combined with other factors—such as high humidity, strenuous activity, or prolonged exposure—physiologic compensation mechanisms can be overwhelmed. The National Weather Service’s (NWS’s) Heat Index—a measure of perceived temperature derived from the ambient temperature and relative humidity and based on work originally conducted by Steadman (1979)—is an imperfect but useful tool in determining potential health threats.

Some research has shown that certain disorders of the kidney, liver, heart, digestive system, central nervous system and skin may be linked to heat exposure. However, there is no conclusive scientific evidence linking such effects and long-term exposure to heat. The exception is damage to the eye, in particular the lens, from radiant heat and infrared radiation. Occupations at risk for eye damage include glass manufacturing, foundries, ceramics, bakeries, and outdoor activities in brilliant sunshine without sunglasses (particularly at high elevations). Other probable health effects that have been reported include chronic heat exhaustion, sleep disturbances, and susceptibility to minor injuries.

When heat stress is more extreme, the possible health effects include:

(1) Heat Edema: Heat edema is swelling which generally occurs among people who are not acclimatized to working in hot conditions. Swelling is often most noticeable in the ankles.

(2) Heat Rashes: Heat rashes are tiny red spots on the skin, which cause a prickling sensation. The spots are the result of inflammation caused when sweat glands become plugged.

(3) Heat Cramps: Heat cramps are sharp pains in the muscles that may occur alone or be combined with one of the other heat stress disorders. The cause is salt imbalance resulting from the failure to replace salt lost with sweat. Cramps most often occur when people drink large amounts of water without sufficient salt (electrolyte) replacement.

(4) Heat exhaustion: Heat exhaustion is caused by excessive loss of water and salt. Symptoms include heavy sweating, weakness, dizziness, nausea, headache, diarrhea, muscle cramps, and more.

(5) Heat syncope: Heat syncope is heat-induced giddiness and fainting induced by temporarily insufficient flow of blood to the brain while a person is standing. It occurs mostly among unacclimatized people. It is caused by the loss of body fluids through sweating, and by lowered blood pressure due to pooling of blood in the legs.

(6) Heat stroke: Heat stroke and hyperpyrexia (elevated body temperature) are the most serious types of heat illness. Signs of heat stroke include body temperature often greater than 41°C, and complete or partial loss of consciousness. The signs of heat hyperpyrexia are similar except that the skin remains moist. Sweating is not a good symptom of heat stress as there are two types of heat stroke – “classical” where there is little or no sweating (usually occurs in children, persons who are chronically ill, and the elderly), and “exertional” where body temperature rises because of strenuous exercise or work and sweating is usually present.

(7) Acclimatization: Physiological changes which occur in response to several days of heat exposure and make the body accustomed to a hot environment.

(8) Dehydration: Loss or deficiency of water in body tissues caused by sweating, vomiting or diarrhea. Symptoms include excessive thirst, nausea, and exhaustion.

(9) Heat strain: Physiological and behavioral responses of the body as a result of heat exposure.

4.3 Cold Stress

Cold stress has been defined as “a thermal load on the body under which greater than normal heat losses are anticipated and compensatory thermoregulatory actions are required to maintain the body thermally neutral”.

4.4 Effects of Cold Exposure

Workers who are exposed to extreme cold or work in cold environments may be at risk of cold stress. The US Center for Disease Control and Prevention explained: “Extreme cold weather is a dangerous situation that can bring on health emergencies in susceptible people, such as those without shelter, outdoor workers, and those who work in an area that is poorly insulated or without heat. Prolonged exposure to cold will eventually use up your body’s stored energy. The result is hypothermia, or abnormally low body temperature. A body temperature that is too low affects the brain, making the victim unable to think clearly or move well [9]”.

Health problems associated with cold exposure include:

(1) Frostnip: Frostnip is the mildest form of a freezing cold injury. It occurs when ear lobes, noses, cheeks, fingers, or toes are exposed to the cold and the top layers of the skin freeze. The skin of the affected area turns white and it may feel numb. The top layer of skin feels hard but the deeper tissue still feels normal (soft). The top layer of skin sometimes peels off the affected area.

(2) Frostbite: Frostbite is caused by exposure to extreme cold or by contact with extremely cold objects (e.g., metal). It may also occur at normal temperatures from contact with cooled or compressed gases. Frostbite occurs when tissue temperature falls below freezing (0°C), or when blood flow is obstructed under cold conditions. Blood vessels may be severely and permanently damaged, and blood circulation may stop in the affected tissue. In mild cases, the symptoms include inflammation (redness and swelling) of the skin in patches accompanied by slight pain. In severe cases, tissue damage without pain, or burning or prickling sensations and blistering can happen. Frostbitten skin is highly susceptible to infection, and gangrene (local death of soft tissues due to loss of blood supply) may develop.

(3) Hypothermia: This is the progressive lowering of the body’s core temperature from 37°C, where unconsciousness followed by death can occur. Hypothermia occurs when the body is unable to compensate for its heat loss and the body's core temperature starts to fall. You first feel cold followed by pain in exposed parts of the body. As the body’s core temperature continues to drop, the feeling of cold and pain starts to diminish because of increasing numbness (loss of sensation). If no pain can be felt, serious injury can occur without the victim noticing it.

As the body continues to cool, muscular weakness, an inability to think clearly, and drowsiness are experienced. This condition usually occurs when the body’s internal or core temperature falls below 33°C. Additional symptoms include shivering coming to a stop, diminished consciousness and dilated pupils. When the core temperature reaches 27°C, coma (profound unconsciousness) sets in.

(4) Chilblains: Chilblains are a mild cold injury caused by prolonged and repeated exposure for several hours to air temperatures from the freezing point (0°C) to as high as 16°C. Where the skin is affected, there will be redness, swelling, tingling, and pain.

(5) Immersion foot: Immersion foot occurs in individuals whose feet have been wet, but not freezing cold, for days or weeks. It can occur at temperatures up to 10°C. The primary injury is to nerve and muscle tissue. Symptoms include tingling and numbness; itching, pain, swelling of the legs, feet, or hands; or blisters may develop. The skin may be red initially and turn to blue or purple as the injury progresses. In severe cases, gangrene may develop.

(6) Trenchfoot: Trenchfoot (or hand) is "wet cold disease" resulting from prolonged exposure in a damp or wet environment from the freezing point to about 10°C. Depending on the temperature, symptoms may begin within several hours to many days, but the average is three days.

The effects of heat and cold exposure are listed in the Table 1.

Table 1: PET index Comfort Intervals [10]

Physiologically equivalent temperatures (PET) (°C)	Thermal perception	Grade of physiological stress
< 4	Very cold	Extreme cold stress
4.1 – 8.0	Cold	Strong cold stress
8.1 – 13.0	Slightly cool	Slight cold stress
18.1 – 23.0	Comfortable	No thermal stress
23.1 – 29.0	Slightly warm	Slight heat stress
29.1 – 35.0	Warm	Moderate heat stress
35.1 – 41.0	Hot	Strong heat stress
>41.0	Very hot	Extreme heat stress

5. METHODOLOGY

The system has been designed to maintain a constant temperature of a dress to provide a better comfort to human. The system operates with the thermoelectric refrigeration system, which operates according to the Peltier effect.

The total set-up consists of a peltier unit or thermoelectric cooling device (TEC 1-112706), heat sink, DC cooling fan and a controller circuit. Other used components are pump, micro-tubes, T-shirt, hydration backpack, temperature sensors (LM 35), Arduino Uno, LCD etc. For automatic operation of the heating and cooling processes, Arduino has been used. A 16x2 LCD display has been used for monitoring the processes. The system operates exclusively with thermoelectric cooling device, which provides cooling as well as heating, when required and no compressor is required.

5.1 Experimental Setup

At first the micro-tube has been attached to the T-shirt by sewing onto the dress. Figure 2 depicts how the micro-tubes are sewn onto the dress. Then the container, which is used as hydration backpack, is insulated very carefully. The pump is placed in the container. One end of the micro-tube is attached to the pump discharge nozzle. And another end of the micro-tube is placed back to the container. The container is filled with water at a desired level. The thermoelectric cooling device (TEC) is placed above the water upper level surface. For this purpose plywood has been used, which is lighter than water and is not getting swept. Heat sink has been attached on the hot surface of the TEC by the thermal paste. Then the cooling fan has been placed on the heat sink.

Here three temperature sensors (LM 35) have been used. The first one measures the container’s water temperature, the second one measures the exit water temperature from micro-tubes and last one measures the environment temperature. All the sensors, cooling fans, TEC and pump have been attached to the controller circuit. The controller circuit consists of five relay, four transistors, some input and output ports. Two types of power supply have been used- one is 6V DC and another one is 12V DC. The 6V DC is used of Arduino, LM 35 and run the relays. 12V DC is used for TEC, cooling fan and pump. A belt has been used for holding the container with the body.

An Arduino Uno has been used to control all the processes and devices. A 16x2 LCD display has been used for monitoring all the temperatures and processes.

Figure 2: Micro-tubes sewn on the dress.

5.2 Working Principle

At first the processing unit (Arduion Uno) reads all the sensors, i.e. the reservoir temperature, water exit temperature and the atmospheric temperature. Then it determines which process will have to run of the following two processes – cooling process and heating process. If the environmental condition is hot, i.e. atmospheric temperature is greater than 25°C the processing unit will run the cooling process. If the environment is cold i.e. atmospheric temperature is lower than 10°C then it will run the heating process. While cooling process is running, the reservoir temperature is kept low as 10°C. And when heating process is running, the reservoir temperature is kept high as 70°C. After reading all sensors, Arduino determines the process and runs the pump. The pump is not run all the time, it will be run only when there is significant difference between the reservoir temperature and water exit temperature. Here "significant difference" means this difference of temperatures can be set by user for his/her comfort. This difference can be varied also. The pump circulates water through the micro-tubes. These tubes transfer heat between body and water. The reservoir temperature is kept constant by running TEC. In cooling process, TEC performs cooling operation and in heating process, TEC performs heating operation. The operations of TEC are determined by Arduino. When TEC runs, there is a huge temperature difference between two sides of the TEC. So in cooling operation, the hot side of TEC need be cooled by cooling fan.

(a) Cooling Process: Frozen ice with some chilled water is stored in the hydration backpack. This chilled water is circulated with a high efficiency small pump through micro-tube which is sewn onto the T-shirt. Heat from the body is transferred into water, which is circulated back to the hydration backpack. The heat is absorbed by slowly melting ice. The temperature of the water stays constant until all of the ice has melted. When all ice has been melted, temperature of the water increases. This temperature is measured by one temperature sensor. If this temperature is higher than 10°C, then thermoelectric cooler is turned on via controller circuit. To save battery power, the pump does not run always. Two temperature sensors are situated at the beginning and ending of the micro-tube. The Arduino calculates the temperature difference. When the difference is higher than recommended value, then the pump is turned on and when this difference is equal to the recommended value, the pump is turned off. Thus the battery power can be saved. With periodic recharging of ice, the system provides continuous consistent cooling regardless of changes in the external environmental conditions.

(b) Heating Process: For heating purpose, the hydration backpack contains hot water. Liquid circulation system is same as the cooling process. The thermoelectric refrigerator, here works as a heat pump, which supplies heat to the hydration backpack. This is done by reversing the current flow to the thermoelectric refrigerator.

5.3 Process Layout

A schematic diagram of the whole process is shown in Figure 3 and how water flows through the micro-tube is shown in Figure 4.

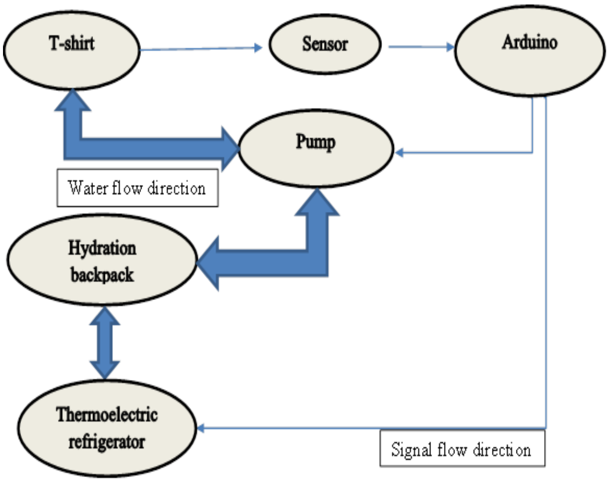

Figure 3: Process layout.

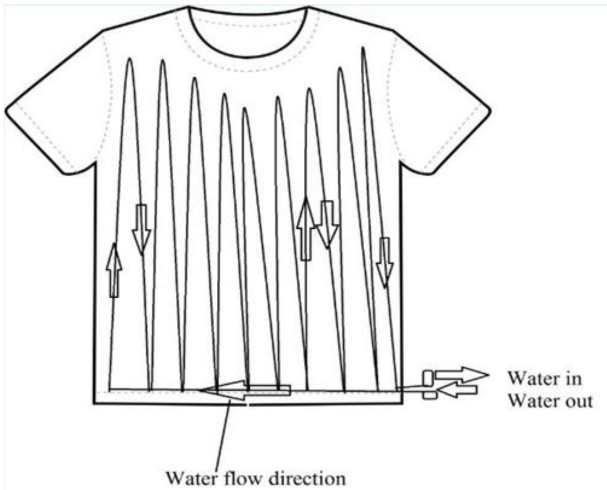

Figure 4: Water flow direction in the T-shirt through micro-tube.

6. RESULTS AND DISCUSION

To study the performance of this dress, the following experiments were carried out. Then data were collected and plotted on the graph. The measured data were hydration backpack i.e. the reservoir temperature, T_{in}, water exit temperature from micro-tube, T_{out}, atmospheric temperature, T_{atm}, and water mass flow rate through the micro-tube, $\dot{m}$. Here heat rejected to or gained, $\dot{Q}$, from the water through the wall of micro-tube by a human has been calculated from collected data.

(a) Exp. 1: This experiment was carried out in hot environment (T_{atm} >30°C).

Case 1: Idle condition: T_{in} = 10°C, T_{out} = 13°C, $\dot{m}$ = 1.67x10^{-3} kg/s

Heat rejected by human body, $\dot{Q}$ = 21 J/s

Case 2: Walking condition: T_{in} = 10°C, T_{out} = 15°C, $\dot{m}$ = 1.67x10^{-3} kg/s

Heat rejected by human body, $\dot{Q}$ = 35 J/s

(b) Exp. 2: This experiment was carried out in cold environment (T_{atm} <10°C).

Case 1: Idle condition: T_{in} = 47°C, T_{out} = 44.5°C, $\dot{m}$ = 1.67x10^{-3} kg/s

Heat absorbed by human body, $\dot{Q}$ = 17.5 J/s

Case 2: Walking condition: T_{in} = 47°C, T_{out} = 46°C, $\dot{m}$ = 1.67x10^{-3} kg/s

Heat rejected by human body, $\dot{Q}$ = 7 J/s

(c) Exp. 3: This experiment was carried out in room temperature (T_{atm} = 25°C).

Case 1: Idle condition: T_{in} = 10°C, T_{out} = 11.3°C, $\dot{m}$ = 1.67x10^{-3} kg/s

Heat rejected by human body, $\dot{Q}$ = 9.1 J/s

Case 2: Walking condition: T_{in} = 10°C, T_{out} = 12°C, $\dot{m}$ = 1.67x10^{-3} kg/s

Heat rejected by human body, $\dot{Q}$ = 14 J/s

All results are summarized in the Table 2.

Table 2: Heat rejected or absorbed by human body in various environment.

Environmental condition	Heat rejection or gain, J/s		Heating process
	Human activity		
	Idle	Walking	
Hot (>30°C)	21	35	Cooling
Cold (<15°C)	17.5	7	Heating
Room temperature (25°C)	9.1	14	Cooling

From the calculations, it has been seen that heat rejection rate of a human increases with the increases of his/her physical activity. Because the physical activity increases, the metabolism rate also increases. So, more heat is released. For this reason, in cooling process, the outlet and the inlet temperature difference increases from idle condition to walking condition, which is plotted in Figure 5. For same reason, in heating process, less heat absorbed by human body which is plotted in Figure 6.

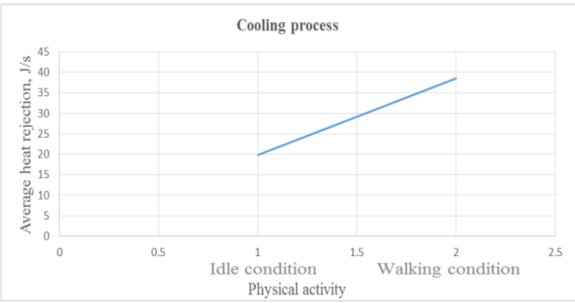

Figure 5: Average heat rejection vs. physical activity.

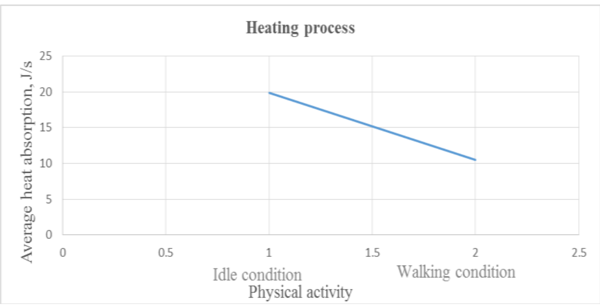

Figure 6: Average heat absorption vs. physical activity.

7. CONCLUSION

Thermal comfort is also very important. Ideally, air temperature should be kept within a range that most people find comfortable. The season, relative humidity, clothing and activity level of building occupants may factor into the comfort zone. In summer, temperatures of 23-28°C are recommended, while in the winter when relative humidity is closer to 30%, recommended temperatures are from 20-25°C. But everywhere it is not possible to keep this comfort zone. Specially, in outdoor activities, working near furnace – where central air conditioning is not possible, this thermal dress is very compatible. It is perfect for sports, racing, motorcycling, bicycling, running, construction and industrial purpose. No matter how hot and humid it is outside or very cold environment, one will be in one's own personal "microclimate of conditioned either cooling or heating".

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9. NOMENCLATURE

Symbol	Meaning	Unit
T	Temperature	(°C)
$\dot{m}$	Mass flow rate	(kg/s)
$\dot{Q}$	Heat transfer rate	(J/s)