

ENERGY HARVESTING USING AN ABSORBABLE BODY HEAT THERMOELECTRIC GENERATOR

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Abstract: *The aim of this paper explains why thermoelectric generator (TEG) embedded in a wearable black synthetic underwear can be used to generate electric energy from heat energy from the human body which is use for various purposes such as charging of phone, rechargeable ear pieces, radio, touch light etc. The method used to carry out this research work was the principle of Seebeck effect (temperature converted into current). Black underwear was used as an absorber of heat from the body. Energy harvester called thermoelectric generator was used to scavenge heat from the human body. Heat loss from the human body can occur in form of conduction, convection, radiation and evaporation. Electric energy is generated through the use of electronic device called thermopiles. The TEG contains 16 small size thermopiles which are connected in series were sewed together with the underwear. The current, voltage and temperature were calculated and recorded. This shows that TEG power modules were used to harvest the heat from the body. It could power 230 μ W at temperature of 18°C. But when embedded in black synthetic underwear at stationary position, at 17°C it was already at 750 μ W due to heat absorb by the black underwear. The power increased immediately at jogging and running. Also various tests were carried out on the texture and color of the fabrics. Temperature, current, voltage and distance cover from standing position to sprinting position were all plotted against power. There was increase in power as more heat was dissipated from the body. In conclusion, the hidden TEG imbedded in the black synthetic underwear cloth did not bent after use on several occasions. Several colors of fabrics materials such as black, red, yellow and white were tested, to show how much heat that can absorb the most. Surprisingly black absorb more.*

Keywords: *Thermoelectric generator, Black synthetic underwear, Heat energy, Electric energy, Human body*

1. INTRODUCTION

Renewable energy has been major problem of concern globally. The increase in the demand for fossil fuel that lead to environmental hazard like air pollution, water pollution and land pollution which have been one of major issue researchers are trying to look for alternative sustainable and renewable source of energy [1]. In developing country like Nigeria, fossil fuel has been the major sources of supply of electricity. Industries, offices, institutions, commercial centers and household buildings all depend on fossil fuel to carry out their daily activities [1]. These have resulted to noise and air pollution which have cause health issues like deafness, cancer and other dangerous diseases due to inhaling of harmful gases and direct contact with human skin. As technology advances, an increase in population will also result to increase in demand for fossil fuel which will continues to rise rapidly resulting to release of greenhouse gases and degradation in the environment [1]. But with the introduction of alternative sources of renewable energy like wind, dynamo, water, solar, tide, acoustic and many more are still under research study [1]. The mentioned alternative renewable energy has its limitations. For recent solar energy require sunlight for electric power supply. Also water, wind and kinetic energy are all needed for electric power generation. These sources of renewable energy have been used, explored, harvested, and developed which now serves as a solution to current and future problems [1]. In recent years, one major sources of renewable energy is thermoelectric power generation which harvested wasted heat energy to generate electricity [1]. It has been shown over the years that thermoelectric power generation is pollution free, clean energy competitor with no release of greenhouse gases and cost less. They are also known as green technology because it does not produce any harmful waste during electric power production [1].

2. METHODOLOGY AND MATERIALS

2.1. Thermoelectric Generator

Thermoelectric generators (TEGs) are device considered from many generators as energy harvester. The main purpose is to generate electricity from wasted heat energy in renewable and reliable way [1]. In this research work, a flexible thermoelectric generator is used instead to replace electrical power system such as battery and capacitor. There are many advantages thermoelectric generator has over other sources of renewable energy [1]. They are as follows: - less space is required, increase in efficiency of 5% to 8%, small in size, green technology, alternative source of power supply etc. TEGs can serve so many purposes such as IC engine, computer system, furnace, water tube that hot, refrigerator and human body.

2.1.1. Theory and Technological Principle

Electric current are produce as a result of electron in motion in circuit while electric voltage is the propelling force that drive the electric current [2]. Not until 1821 a German physicist called Thomas Johann Seebeck discovered Seebeck effect. Seebeck effect is when heat energy is directly converted to electricity [2]. This is caused when two dissimilar metal join together to form a joint with a temperature difference between the joints. This produced electric voltage and magnetic effect. This is because of the electron energy level shifting between each dissimilar metal forming a potential different between them [2]. In Figure 1, N and P type are connected in parallel thermally, but should be in series electrically in the circuit. The hole flows in opposite direction to the electron flow, forming a series aiding as a result of the pellet generating current potential not opposing one another [2].

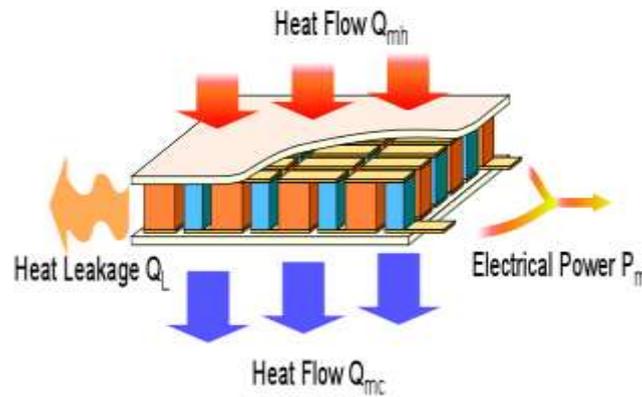


Fig.1. Shows the heat leakage from a thermoelectric generator module which is as a result of heat loss [2].

2.1.2. The Seebeck Effect

This is the process whereby temperature different caused by two different conductors producing voltage different. These two different conductors are known as semiconductors material [2]. The voltage produced is called Seebeck voltage. Seebeck coefficient is denoted as S

$$S = \frac{(-\Delta V)}{\Delta T} \quad (1)$$

The equation above, with different parameters used such ΔT denote different in temperature at the both the cold and hot side, ΔV denote different in voltage. It important to note that electron charge is negatively charge which comes from flow of current. This indicates that N- type material carries negative Seebeck while P-type material carries positive Seebeck. So therefore, thermoelectric generator contains both N-type and P-type semiconductor that generate current [3]. They are called thermopiles. The efficiency of the thermoelectric generator shows how much workload it can carry and how productive it can generate electric current. It denoted as (Z):

$$Z = \frac{S^2 \times \sigma}{K} \quad (2)$$

The efficiency (Z) is known as Seebeck coefficient; (K) is known as thermal conductivity and σ is known as electrical conductivity. It should be noted that efficiency depends on Seebeck coefficient. Mostly materials used for semiconductor are bismuth telluride [3]. Reason is because; it has low thermal conductivity and high electrical conductivity [3]. The efficiency is approximately one.

2.1.3. Maximum Power Thermoelectric Generator

Thermopile is used to generate the maximum power needed on electrical load [4]. It is denoted below as in an equation 3

$$P_{max} = Z \Delta T^2 / 4R_{tp} \quad (3)$$

P_{max} Is denoted as maximum power, Z is the figure of merit, S is Seebeck coefficient, σ is electrical conductivity, k is thermal conductivity, ΔT is temperature difference, and R_{tp} is thermal resistance at its maximum power [4]. W is known as the heat flow passing through the thermopile. The equation is shown below.

$$P_{max} = Z W^2 R_{tp} / 4 \quad (4)$$

2.1.7. Conversion Efficiency of Thermoelectric Generator

To get the efficiency, the power produced by thermoelectric effect between the two thermo legs having different Seebeck coefficients is denoted as $(\alpha_{m1}$ and $\alpha_{m2})$ which combine together to become thermocouple (TC) [4]. The equation for temperature difference is shown below as

$$\Delta T_{TEG} = T_{hot} - T_{cold} \quad (5)$$

This lead to generating open circuit voltage denoted as V_{OC} with the equation shown below as

$$V_{OC} = \alpha \cdot \Delta T_{TEG} \quad (6)$$

It is noted that $\alpha = \alpha_{m1} - \alpha_{m2}$ is the Seebeck coefficient that is combined together to make up TC [4]. Previously discussed, the maximum output power which denoted as P_{max} is used for matched electrical load together with ΔT_{TEG} to form equation 7 below

$$P_{max} = \frac{V_{OC}^2}{4 \cdot R_{el}} \cdot (\Delta T_{TEG})^2 \quad (7)$$

With R_{el} denoted as internal electrical resistance, knowing the thermoelectric power conversion requires figure of merit ZT to be rewritten as module figure of merit (ZT_m) to form equation 8 below [4].

$$ZT_m = \frac{(m \cdot \alpha)^2 K_{TEG}}{R_{el}} \quad (8)$$

Since K_{TEG} is denoted as thermal resistance. If it assume that ideal Carnot engine was connected through using a thermal interface resistance to a heat reservoir for rein stance the human body (T_{body}) with a heat sink (T_{amb}) [5]. These make up the equation below as

$$\eta_{ideal} = 1 - \sqrt{\frac{T_{amb}}{T_{body}}} \quad (9)$$

When thermoelectric generator that has electrical and thermal are matched together, it important to consider the thermal conduction and joule heating making the conversion efficiency of the power output to be reduced in an optimized system [5]. It is shown below in equation 10

$$\eta_{real} = \eta_{ideal} \frac{ZT}{(1 + \sqrt{1 + ZT})^2} \quad (10)$$

The right of the equation is denoted as the material properties. Before DC-DC conversion, it said that ZT and maximum output power depend one another in fully arrange system [6]. Also when ZT is higher it generates higher power output. To produce total conversion efficiency η_{total} with application of core body heat, there is a need for electric conversion and thermal efficiency to be added together [6]. This is shown in the equation below as

$$\eta_{total} = \eta_{real} \cdot \eta_{el}. \quad (11)$$

2.2. The Mechanism Process for Harvesting Heat Energy from Thermoelectric Generator and DC-DC Converter Module.

Despite small current, voltage, electric power output is generated from flexible thermoelectric generator. The DC to DC converter was used to boost and to stabilize the output voltage harvested from the thermoelectric generator [7]. DC to DC converter accumulates the power output and then stores it in a super capacitor for charging electric devices [7]. The supercapacitor serves as an electric storage to store energy for use. When low thermoelectric output voltage, generate voltage as low as 20mV, it is boosted by the DC-DC converter to a voltage output of about 2.2V to 5V.

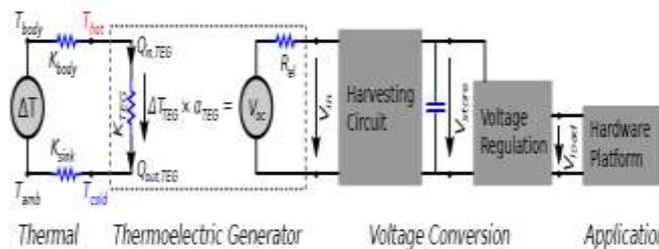


Fig.2. General View the system from the body to place of application [7].

2.2. Thermoelectric Generator Classifications and Specification

In this research, thermoelectric power generating module (TEG) that was used is called Adol. Adol is the brand name of this device. With a certificate number of ISO9001. CE and model number of TEG1-127-1.0-1.5-250. It can produce DC electricity at all time provided there is temperature different at both end of the module.

Table 1. Shows more details of thermoelectric module specification

No.	Part number	TEG1-127-1.0-1.5-250
1.	Hot side temperature (Degree C)	250
2.	Cold side temperature (Degree C)	30
3.	Voltage open circuit (Volts)	10.0
4.	Matched load resistance (ohm)	6.6
5.	Matched load output Voltage (Volt)	5.0
6.	Matched load output current	0.8
7.	Matched load output power (Watt)	3.8
8.	Heat flow across the module (Watt)	76
9.	Heat flow Density (Wcm^2)	8.4
10.	AC resistance (Ohm) under 27 degree C	4.1

2.3. Body Heat Flow

For any flexible thermoelectric generator to work efficiently, it requires a heat source as a major source of supply [8]. The human body can serve as a thermal load that can produce energy such as magnetism, electricity, wave, and even heat energy. The normal temperature for a healthy person is between 36.2°C and 37.2°C. There is a part of the human brain that regulates body temperature. It is called the hypothalamus [8]. More energy is being exerted by the body to keep the body at a particular temperature. At 31°C to 35°C of normal environment, the internal core temperature is adjusted and regulated but the skin temperature remains unregulated. Scientist believes that normal body temperature is 37°C while other medical researcher believes it is 36.8 °C [8]. It should be noted that the human body always produce heat and should always loss that heat either through conduction, radiation, convection and evaporation [8]. Every day, the human body losses 80% of waste heat through energy cost.

2.3.1. Conduction

Conduction is when two object transfer heat in between them [8]. It is shown below in equation 12

$$\Delta Q / \Delta t = k A \Delta T / \Delta x, \quad (12)$$

Where ΔQ is rate of flow in watt, k is thermal conductivity, Δt is time in second, A is body area, Δx is material thickness and ΔT is temperature in kelvin.

2.3.2 Convection

Convection is when a fluid is moving transfers heat between them due change in density in the fluid [8]. It can also occur in object surface, gas. It is shown below in equation 13.

$$\Delta Q / \Delta t = 14.5 A \Delta T \quad (13)$$

ΔQ denoted as the heat flow in convection rate measure in watts; A is denoted as square meters and v as wind speed measured in meters per second.

2.3.3. Radiation

Radiations occur when heat transfer from hot object to a cool object without any contact that is physical [8]. Infrared wavelength is emitted from the body due to agitation of molecules. The human body has the able to transmit, reflect and even absorb radiation easily. It is shown below in equation 14.

$$\Delta Q / \Delta t = \epsilon \sigma A (T_b^4 - T_a^4) \quad (14)$$

ΔQ denoted as radiation current measured in Watts, ' ϵ ' is known as emissivity, independent on colour of the human skin the emissivity is known as 0.97, σ is denoted as "Stefan-Boltzmann's" constant measured in $(5.67 \times 10^{-6} \text{ W} / \text{m}^2 (\text{K})^4)$ and T denotes temperature measured in kelvin, b is known as body while a is the ambient temperature.

2.3.4. Evaporation

Evaporation occurs when sweat stops in the body. Thermal current is related to rate of sweat because of latent heat of vaporization is associated [8]. The equation 16 is shown below.

$$\Delta Q / \Delta t = (\Delta m / \Delta t) L \quad (15)$$

2.4. Heat Flow In Polyester Fiber Clothing

There are two properties that explain the effect of clothing on heat exchange [9]. They are as follows:

2.4.1. Thermal insulation

Thermal insulation in clothing is determined by the type of material and the construction of fabrics properties used. It is affected by the still air layer, trapped air, air layers and the thickness of the fabrics. The mathematical equation in the equation is shown below

$$R + C = \frac{(t_{sk} - t_a)}{I_{Tot}} \quad (16)$$

Where t_{sk} denotes skin temperature, t_a denote ambient temperature, I_{Tot} denote thermal insulation ($\text{m}^2 \text{C/W}$)

$$E = \frac{(P_{sk} - P_a)}{R_{et}} \quad (17)$$

Where R_{et} is denoted as evaporative resistance ($\text{m}^2 \text{kPa/W}$), p_{sk} is denoted as skin water pressure vapour (kPa) finally P_a is known as ambient water pressure vapour (kPa).

$$I_{Tot} = \frac{t_{sk} - t_a}{R + C} \quad (18)$$

It is also known, that the total valve for insulation is the sum of the valve for clothing insulation (I_{cl}) while insulation surface air layer is known as (I_a). It is also known as nude body surface. Correction should be made to increase surface layer (f_{cl}) when cloth is worn on the body. The equation is shown below in equation 19.

$$I_{Tot} = I_{cl} + \frac{I_a}{f_{cl}} \quad (19)$$

Thermal manikin measures thermal insulation accurately. When $R+C$, t_{sk} and t_a valves are measured at stable condition, the climate channel and insulation produce equation 20. Also the valves of I_{Tot} and I_{cl} are standardly measured in a static, standing manikin condition. The valves mainly used for dressed person that are standing upright in still air [9].

2.4.2 Evaporative Resistance

Evaporative resistance is known for its ability to resist moisture transfer heat into fabrics. Fabrics are well known by their physical properties which are size pores and its thickness in air layer passage [10]. The equation is shown below

$$R_{et} \frac{P_{sk}-P_a}{E} = 0.06 \frac{I_{Tot}}{i_m} \quad (20)$$

Subjects are used directly for measuring evaporative resistance in clothing. Evaporative resistance can also be measured in permeability index of fabric (i_m) and thermal insulation [10]. To measure permeability index, there is the need to use sweating hot plate or sweating thermal manikin. According to equation 21, P_{sk} this denoted as sweating thermal manikins are few and difficult to measure. The diagram below explain the relation between the skin, air, polyester fabrics and it environment.

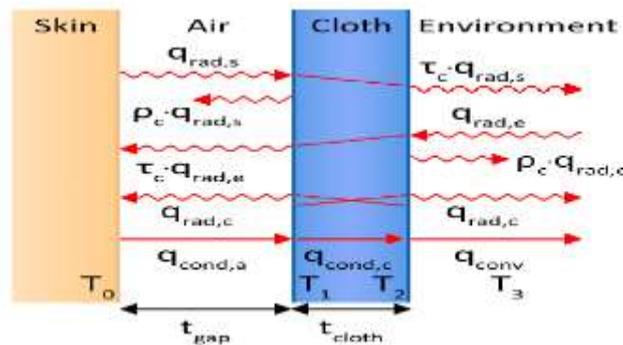


Fig.3. Model shows heat transfer and analysis on how heat is released from the polyester underwear of body into the ambient environment. Heat transfers from the human body are in form of conduction, radiation and convection [9].

3. RESULT AND DISCUSSION

3.1. Test To Show Which Fabric Absorb Most Heat

The named fabrics such as cotton, linen, silk, polyester were used. To test for it absorbing power, a cooled ice block was used of about 1kg. Each of the fabrics was exposed to heated electric bulb of 100 watt in 20 minutes with the ice block imbedded in them. It was observed, that ice block was completely melted in the polyester, and least in cotton but partially in silk. This shows that polyester can absorb more heat.

3.2. Test To Show Which Colour Absorb Most Heat.

In the test, different colors of polyester fabrics were used such as yellow, black, green, white, red, and orange. They were all wrapped with thermometer each and put in a light box. It was exposed to heat lamp of about 100 watt for about 10 minute. The experiment was repeated for 4 times. The result shows that the thermometer increases the most with black fabrics, follow by green, and red, white. The least was yellow. It was black that absorbed the most heat compare to the rest. And yellow absorb the least. This shows why in this research black was used as the right material for absorbing heat emitted from the body to the flexible thermoelectric generator. There were no heat losses.

3.3. Fixing Of Thermoelectric Generator Inside Polyester Underwear

This research, shows that there four major methods of fixing thermoelectric module into polyester underwear. This is shown in the figure 4 below. The thermopile was fixed inside 0.3 mm thick black polyester underwear. To help the thermopile against unnecessary shock, thermal insulating pillars of about four in number were used of about 1 mm wide. Shown below in figure 4 a below [7]. First method of fixing the thermopile, the hot plate was position directly in contact with the skin using a polyester fiber textile. For the cold plate it was positioned 4mm from the cotton used as a layer. Fig.4a. All through, the cold plate worked so well in this research meaning both the hot plate and cold plate were involved in exchange of heat together with ambient air.

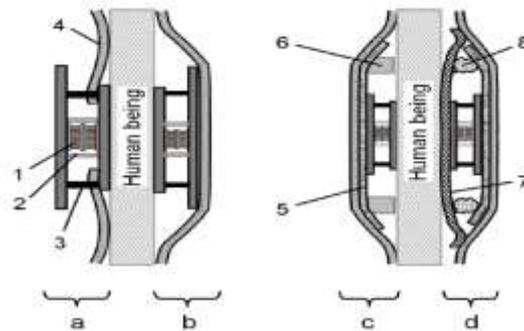


Fig.4. (a) to (d) explains the four major methods to fixing thermopile in the polyester underwear. The numbers shows: (1) thermopile, (2) encapsulated in a polyethylene, (3) thermal insulating spacers (4) polyester textile, (5) heating radiating cotton fabric layer, (6) black colour foam (7) heat absorbing polyester fabric layer, and (8) cotton wool as based spacers. (a) Thermopile that was made to pass directly through the black polyester fiber (b) thermopile was position ally fixed under the black polyester fiber (c) The layer that spreads the heat was glued directly to cold plate, together with the cotton fabric layer while with use of the foam spacer help in keeping reasonable distance apart between heat dissipating layer and skin (d) Additional layer of black polyester fiber was glued to the thermopile and sewed inside together.

The second method of fixing the thermopile was positioning it between the black underwear and the skin. The device was sewed together on the chest from a distance of 9 to 11 cm below the chin level. Using a polyester material is because its possess heat absorbing power. It was tried in three position 1) fixed firmly and tightly to cold plate of the thermopile, Fig.4, 2) air gap was of distance of 5-10 mm was allowed between the cotton wool and the cold plate and 3) The cotton wool was position at both right and left of the black polyester underwear providing space for thermopile to be completely expose. This is almost the same method applied to fig.4a. It was observed that the power produced was about approximately 95% the same compare to method applied in first and third. But in the case of the second method using air space and cotton wool, it was observed that the power produced was worst and was only half the power produced compare to the first method and the third method used. The reason for this was because, cotton wool which has the ability to radiate heat compare to when polyester fiber was used which have the ability to absorb heat and was used in first and third method. Another observation was made; when the cotton fiber with large area was as the radiator of heat and then polyester fabric was sew inside the underwear with the cold plate of thermopile glued to the polyester fabric, as shown in fig.4c. When the both figs.4b and fig.4c were observed closely, it showed 30% increase of power. This was because of the heat dissipated layer made of polyester fabric absorbed more of the heat. Finally another observation was shown in fig.4d; Additional black polyester fabric was used as the textile layer and sewed together with the thermopile and cotton fiber layer glued directly to cold plate. Cotton wool was added at both right and left of thermopile. It was observed, that the power produced was higher compared to others. The power was about 97%. This was due to heat absorbed completely from the body with no heat loss due to black color used also to absorb the heat. The thermopile was completely hidden between two polyester layers. It was light, and comfortable to wear by the user. This method was best adopted for this research because of the positive result that was observed. In this research, sixteen thermopiles were fixed on back and front side of underwear. The hot plate was joined to a piece of black polyester and wired as shown in fig.5 when arranged using fig.4d.



Fig.5. Shows the additional polyester textile used to assemble four of sixteen thermopiles. They were sewed together and were hidden inside the polyester underwear.

3.4 Evaluation Of Thermoelectric Polyester Underwear Performance

To know the performance of the polyester underwear, a though research was conducted on people. It was tested on people during various activities such standing, walking, working in the office, cycling and outdoor activities. To harvest the power, evaluation on performance of the polyester underwear was carryout using the ambient temperature and distance covered. For about 10

minutes maximum, the ambient temperature was 18°C for both the person standing and walking outside the building. It generated power of 230µW before the power dropped completely to 90µW due to thermal equilibrium. It was observed that at 22°C while in the office, the power was 1m W (1.2 V) and double as soon as the person walked to the corridor of the building. This was because of the effect of the forced air convection and not majorly as a result of metabolic rate while walking. 2m W was generated and double at ambient temperature reduction to 17°C while sitting outside. Further walking lead to the raising of power to 750µ W. It power was higher due to the black colour absorbing the heat from body. There was also an experiment that was conducted to know if power will increase or decrease due to metabolic rate. An outdoor exercise was conducted, using a bicycle that was ride for one hour at a reasonable distance of 4 metre. It is shown below in figure 6

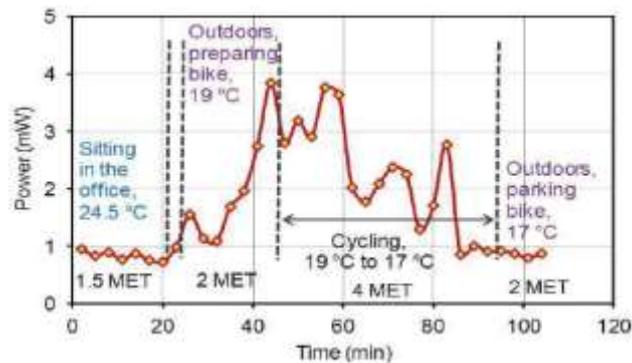


Fig.6. Graphical illustration to show power generated for the thermopile imbedded in a black polyester underwear against time. All activities shown from a sitting to outdoor exercise.

During the cycling, it was observed that actual power drop drastically and finally get to the level of power that was observed in the office initially. It was interesting to know, that after 4 metre of the cycling, the power was the same with that of a person standing. The power was also the same with the person sitting in the office before cycling exercise at a initial distance of 1.5 metre. The experiment shown earlier that power produced from the thermopile have nothing to do with metabolic rate but instead is affect strongly by three major factors which are air speed, the rate of body heat dissipated from the person and the rate of sweating from person. It is interesting to know, that the power increase during the starting period of the exercise was due to air force convection. That about 35 - 45 minutes, there was power increase when the cyclist was in a standing position at a point where there was wind. There was gradual decrease in power due to metabolic rate that result to sweating. The reason for the power drop was due to temperature dropping which resulted to sweating leading to evaporation process.

4. CONCLUSION

Throughout the research study, there was no complain recorded on thermal discomfort during the time of critical study and evaluation on the ambient conditions. It is joined and sewed, looking the same way compare to the underwear brought in the shop. Comfortability is added to underwear with help of the cotton wool layer adding cushion to the skin. It also have a absorbable black polyester material that help to prevent heat loss from the body and the thermopile. The power supply produced from the hidden thermopile is suitable, reliable, efficient, dependable and long lasting .Which can be used to power wearable electric device like phone, head phone, rechargeable touch, and many more.

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