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Design of a fuzzy logic controlled thermoelectric brain hypothermia system

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Abstract: Brain cooling in medicine is the most effective method in protecting brain cells during strokes, heart attacks, and brain traumas. This method, called brain hypothermia, is based on the principle that the brain is superficially cooled under controlled conditions in order to minimize cell death. In this study a helmet was designed to locally cool the brain and an effective controller was designed and tested using fuzzy logic in order to test the effectiveness of the helmet for brain hypothermia. For testing the cooling and heating performances of the helmet, currents between 0 and 60 A were applied to the helmet and its characteristic shape. In considering that the helmet could be exposed to external thermal loads, its maximum cooling capacity at different currents was calculated and found to be 153 W. Two applications were made for the performance test of the controller. Data were recorded for 24 h by setting the inner surface temperature of the helmet to –2 °C and 30 °C. The temperature of the helmet went to –1 °C from 20 °C in 4 min, to 30 °C in 1 min and the temperature remained the same for 24 h. While the system was under balance, a balloon at 20 °C was placed inside and the time the system took to re-balance itself was measured. It was observed that this controller design for a thermoelectric brain cooler can be an alternative method for brain hypothermia thanks to its performance. It was determined that it has advantages over other similar systems thanks to features like it is electrically controllable, has a direct connection to the surface to be cooled and thereby provides faster cooling and heating, its balancing of the thermal loads rapidly applied to the system, and that it is easy to set the cooling and heating speeds via software.

Key words: Brain cooler, hypothermia, thermoelectric

1. Introduction

There are many applications related to selective cooling of biological tissues in the field of medicine [1–8]. A new and useful approach was developed by researchers at the University of Chicago for the treatment of patients after strokes and heart attacks based on cooling organs using specially developed ice slurry [3]. The basic idea is the attainment of the quick cooling, via ice granules mixed in salt solution, of blood that is to be transferred to target organs. Protective hypothermia is achieved for cells and cell death was substantially prevented when organ temperatures were reduced quickly to around 4–10 °C. Quick cooling of blood in sudden strokes and heart attacks may reduce the death of brain and heart cells thereby allowing more time for doctors and health care professionals to save the victims. Cell deaths are caused by hypoxia. Cooling these organs before interrupting blood flow and thus reducing the oxygen requirements of organs gives more time to surgeons for surgery [3].

Local cooling and heating of organs has been used for years and is still used for the treatment of benign tumors, muscle spasms, injuries, and burns [5]. Cooling systems are also used in urology. Urethral cooling

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catheters are used to prevent damage that may take place in the reproduction systems of the prostate due to heat. Dermatology is another field where cooling systems are used. Cooling systems were developed to protect any region of the body from damage when laser treatment is medically applied to that region [6,7].

Cooling systems have been used to protect the brain, one of the most important organs of the body, from the fatal effects of hypoxia. The main purpose of these systems is to cool the blood that goes to the brain quickly in order to prevent the death of brain cells. The human brain can survive without blood, oxygen, and glucose when cooled down to 30–32 °C. The brain can survive for 45–60 min even when the heart stops. The brain needs to be cooled to limit neurologic complications in patients during sudden strokes and heart attacks. For cases where hypothermia cannot be applied, local cooling of the brain prevents neurological damage that may subsequently take place like restrictions in memory, speech, and movement [9–13].

Cooling systems have 3 important stages. The first stage is bringing the temperature of the organ to be cooled to the desired value within the desired period of time. A controlled cooling is required. Otherwise, unstoppable complications may take place. Cooling should be homogeneous and equal for every part of the organ. The second stage of cooling is keeping the organ temperature within the desired range for the desired period of time. In random cooling processes, temperature measurements cannot be precise and cooling speeds cannot be adjusted. For example, brain hypothermia requires the brain temperature to be kept constant for hours, even for days. Dangerous complications may take place if this temperature decreases below the range of 32–34 °C. The third stage of the cooling system is the rewarming process, which needs to be carried out in a controlled manner. The 3 stages of cooling emphasize the importance of system control. Temperatures need to be measured correctly at each stage and signals generated for system control should be selected carefully.

Thermoelectric coolers are among the most important technologies of the 21st century and are widely used in medical fields for reasons such as their electronic control, silent operation, the lack of requirement for any gas for cooling, and their long life. Especially medical material like blood, vaccine, serum, and medicine should be stored at certain temperatures to avoid spoilage. There are portable thermoelectric medical kits developed for this purpose [14]. Thermoelectric cooling or heating is also used in therapeutic pads used for treatment or pain relief. Water is circulated through liquid coolers consisting of solid based modules in a pad to adjust the temperature of the pad. Here, thermoelectric modules are used to cool or heat the water. Another example of using thermoelectric systems in the field of medicine is renal hypothermia applications [15]. Thermoelectric modules were transformed into helmets and used in the cooling process [16–19].

In studies conducted, brain hypothermia is accepted as a treatment method but is performed by means of utilizing different material and methods. Temperature control of the system is one of the significant problems. Regarding the systems that are generally helmet shaped, the air-conditioned water is re-circulated within the helmet for indirect cooling. When the system is exposed to external thermal loads, the duration for re-balancing increases because of the extra time required to heat the water. In the system we designed, thermoelectric modules are in direct contact with the brain through a fine material that is electrically isolated and thermally conductive and that performs the cooling process. Surface temperatures can be changed by simply changing the currents electrically and the heating mode can be activated by changing the polarity. Thus, thanks to this feature, it can also be utilized in the re-heating process.

This study includes the design of a control system for a brain cooling helmet consisting of thermoelectric modules designed to cool the brain locally. The inputs of the thermoelectric modules are current and voltage, while the output is temperature. When this relation is studied, it is noticed that the system is not linear. A thermoelectric module consists of thermoelectric semiconductors. The parameters of thermoelectric semiconductors, like the Seebeck coefficient, and thermal conductivity coefficient, and resistivity, are taken from catalogue data and calculated when the system is not operating. These thermal parameters are calculated using many of the known methods. However, only evaluating the thermal parameters of an operating system causes errors [20]. Measurement of an operating module is important for designing an effective control system. The soldering techniques used for thermoelectric modules and conductors also have an impact on performance. Since the system is not linear and there are too many parameters affecting control, the controller design was made using fuzzy logic designed for systems with linear control techniques like P (proportional), PI (proportional-integral), PID (proportional-integral-derivative). A full bridge circuit was used for the flow control of the helmet. An H bridge circuit can adjust the output flow strength by changing the task duration of the PWM (pulse width modulation) signal. A PIC (peripheral interface controller) 18F4520 microcontroller was used as PWM generator. Temperature, flow, and tension values measured via thermocouple were transferred to a laptop computer using an RS232 port. An RS232-USB (Universal Serial Port) port converter was used for this purpose. These values measured on laptop computer can be recorded on a database and tracked online.

2. Materials and methods

2.1. Materials

Any thermoelectric device or circuit basically contains a module made up of thermoelements. A thermoelement consists of n and p type thermoelectric semiconductors serially connected via a conductor. These are negative and positive terminals of the thermoelement. Thermoelements also make up a module via a serial connection. If a DC (direct current) voltage such as that shown in Figure 1 is applied to a thermoelement, charge carriers pass from the upper copper with a low energy level to the semiconductor. This will reduce the temperature of the upper copper. Regarding the lower copper, load carriers from high energy levels to low energy levels will heat the lower conductor by transferring the excess energy to the lower conductor. During this transfer heat will be adsorbed from the cooling surface and temperature of the surface where heat is pumped will increase. If the direction of the flow applied to the circuit is changed, the cooling surface warms up while the warming surface cools. If the T_1 temperature is kept constant by radiating the heat exposed on the hot surface of an operating thermoelement by any heat transfer system, the cold surface temperature is reduced to a certain T_2 value depending on the passing current, I.

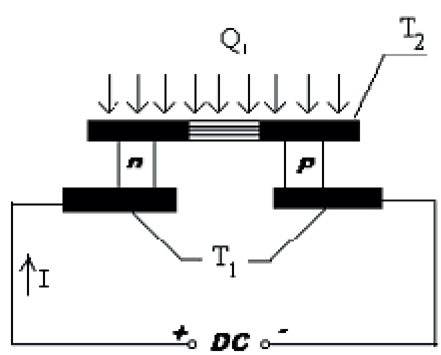

Figure 1. Structure of thermoelement.

As can be seen in Figure 1, the thermoelements that were used are structurally flexible. There is a flexible formation between negative and positive terminals. This allows their full contact area on surfaces to be cooled, thereby providing homogeneous cooling. This is not possible in solid based modules. Dozens of thermoelements have electrical serial thermal connections to obtain thermoelectric modules in different sizes for different purposes.

Temperature reduction speed during brain cooling is important. Temperature reduction should be equal at every stage. After patients start hypothermia, they need to be cooled slowly with a thermal gradient not more than 10 °C. If cooling is slow in patients, it is clinically proven that the heart is not in fibrillation up to a rectal temperature of 22–24 °C. Excessive cooling speed causes excessive loading and fibrillation of the heart [21,22]. Making the helmet from thermoelectric models is very important for the balanced distribution of cooling. A helmet consisting of 70 flexible thermoelectric modules provides cooling from 70 different points of the skull, which allows balanced cooling. The same is valid for the rewarming process.

As shown in Figure 2, the thermoelectric (TE) brain cooler is designed like a motorcycle helmet with the thermally parallel electrical serial connection made up of 70 flexible thermoelectric modules. The operation voltage of these modules is 0.1 V and their optimum flow is 40 A. Seven volt DC voltages are required to drive all subunits where modules are serially connected. A flexible thermoelectric module is used in the design of the brain cooler. The flexible joint technique reduces the thermomechanical voltages caused by the temperature difference to zero and ensures a solid thermoelectric module as well as guaranteed operation time. An important advantage of using a thermoelectric module is that it consists of separate flexible modules and is easily adapted to the shape of the area to be cooled. Its internal surface is coated by a material with high heat conductivity and low electrical conductivity. The external surface is equipped with water channels for water circulated by a water circulation system. It can be easily adapted to the human head due to the structure of flexible thermoelectric modules.

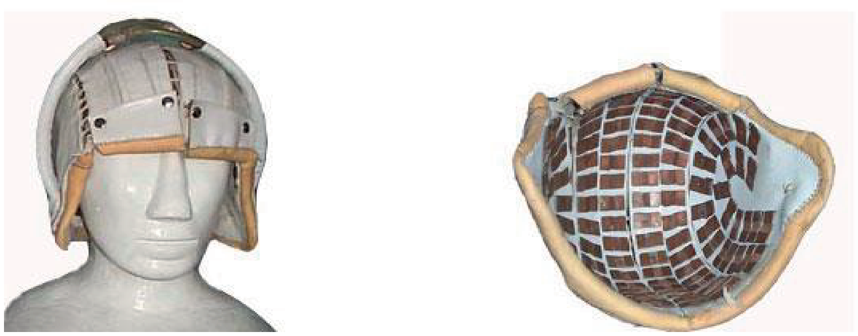

Figure 2. Thermoelectric helmet.

2.2. Method

2.2.1. Hardware

Figure 3 includes the block diagram of the designed system.

Helmet: The helmet consists of 2 parts. Each unit consists of 35 thermoelectric flexible thermoelements. A flexible connection is made at the joint to continue p-n-p-n connection. These units can be electrically separated and controlled as a whole when necessary. A separate power source and driving circuit are designed for each unit of the helmet. These units can operate independently in heating or cooling mode. One part can be heated while the other is cooled.

Water circulating system: The system basically adjusts the internal surface temperature of the TE brain cooler. The external surface temperature of the TE brain cooler can be fixed by circulating the water that is air conditioned by a water circulation system.

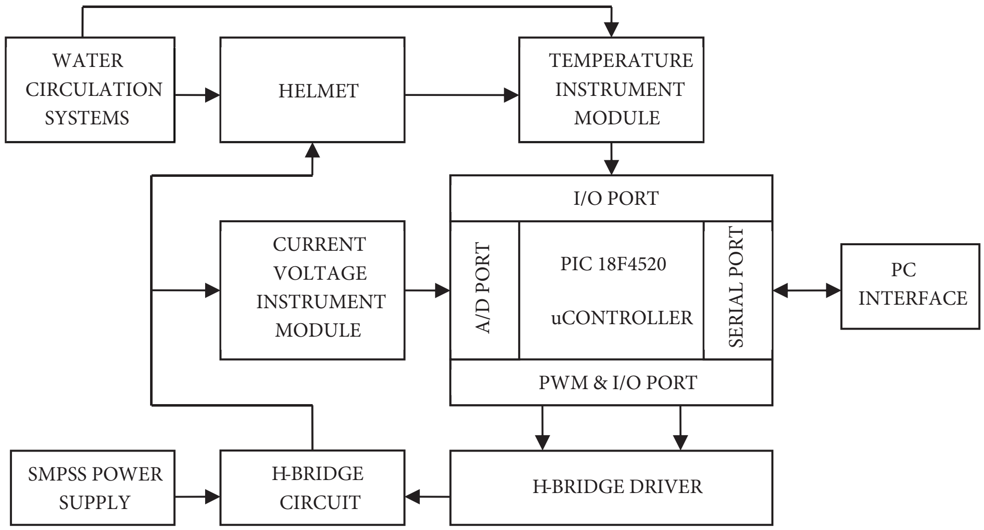

Figure 3. Block structure of the system.

Measurement systems*:* The temperature measurement module can measure the temperature at 4 different points within the helmet, the temperature of water within the water circulation system and temperatures at 2 extra points. The 2 extra measurements were included in the system to measure temperatures inside the rectum, or the ear that can provide the temperature closest to brain. These temperature probes have been excluded from the study. One of the most important points in the designed device is the temperature measurement unit. The inputs of the thermoelectric brain cooler are current and voltage while the output parameter is temperature. The temperatures of the hot and cold surfaces of the module in thermoelectric systems are important. Our device uses a closed water circulation system to fix the hot side temperature. Therefore, the hot side temperature is also measured when the water temperature is measured. Water enters and exits in parallel to and from each part of the designed helmet. Even though the external surface temperature of each part is the same, internal surface temperatures may vary due to the physiological structure. Therefore, temperatures at 4 points are measured. This project uses a MAX6674 with thermocouple digital convertor circuit and cold point compensation. The experimental setup is shown in Figure 4.

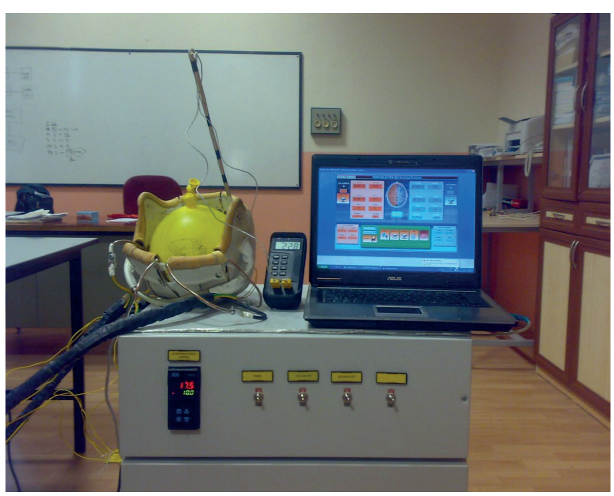

Figure 4. Experimental setup.

Weidmuller's current and voltage tracking modules with the capacity of measuring flow and tension via the Hall effect were used in order to measure flow and tension values applied to the thermoelectric brain cooler. Transfer of temperature data via a serial port after reading with an analogue to digital port occurs at around 100 μs. Since temperature measurement is made at 5 points, information data will be transferred to the computer at 500 μs. The 500 μs time is recorded together with current and voltage data. A 200 ms time is needed for calculating PWM period duration according to fuzzy logic rules after evaluating this information by the computer software, transferring to the microcontroller, and adjusting the current applied to the helmet with the bridge driver by generating PWM signals with microcontroller. A time of 0.2 s is necessary to adjust current and voltage values according to the measured values in total. Figure 5 includes the interface designed for the device.

Figure 5. Device control personal computer interface.

When there is an anomaly in the water temperature for any reason, even if the control process is started, or when the heat value of the helmet is above or below the limit values, or when the operator pushes the stop button, the current applied to the helmet is automatically stopped. The system continues to run only in reading mode until the control button is pressed again.

H bridge driver and circuit: A 7 V 50 A switched power supply is connected to the input of the full bridge driver designed with IGBT (insulated gate bipolar transistor) modules. The full bridge driver circuit can be controlled for the period of the duration of the signal with impulse width modulation. PC (personal computer) software coded in visual basic programming language on a PC calculates a PWM period duration according to the difference between the measured and adjusted values. Required PWM signals are applied to the driver circuit using a PIC 18F4520 microcontroller with 4 PWM outputs. This allows the current value to be applied to the TE brain cooler to be determined. A power supply with a switched-mode power supply mode and a higher quality output was used in feeding the TE brain cooler. A full bridge circuit consisting of 4 IGBTs was used in the driver circuit.

2.2.2. Software

The software can also record when required. Parameters like error, error change, PWM period duration, current and voltage applied to helmet, hot surface temperature, cold surface temperature, and temperature difference can be recorded on a second database when desired. The device control interface is shown in Figure 5.

Fuzzy logic was used in determining the PWM period durations. The principle diagram is shown in Figure 6. Fuzzy logic is a technique that effectively allows controlling of nonlinear systems and it is used in many areas. Fuzzy logic gives programming some abilities specific to humans, such as decision making, and it subjectivity tolerates negative effects likely to be found in the system's characteristic structure. Another superiority of fuzzy logic is that its performance never changes, even in cases where it is impossible to establish mathematical modelling of the system. It allows an easy controller design and, because microprocessor technology is very developed nowadays, the costs are feasible.

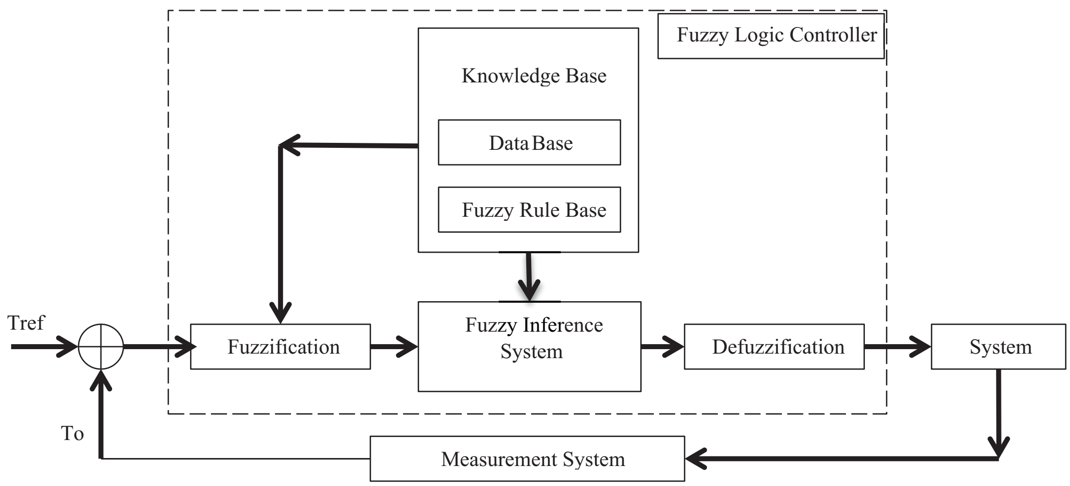

Figure 6. Fuzzy logic control diagram.

In the model designed for controlling the system, 5 membership functions were selected for each input variable and defined by a triangular type function. The system includes 2 inputs (error, error change), 1 Mamdani type output (PWM-pulse width modulation), and 25 rules. "And" operator and min-max fuzzy inference method are among the rules used (Figure 7). The output of this system was realized using the MATLAB program and compared to the outputs provided by the software and so checked. It was seen that the outputs of the software prepared exactly matched up with the outputs of MATLAB Simulink.

A microcontroller was used to produce the PWM signals between the PC software and the system. The PC communicates with the microcontroller and receives the temperature values from the system and divaricates to the subprogram by computing the error and error change amounts. A subprogram performs the required calculations by using the limit values of membership functions previously recorded in the database and calculates the PWM change rate. This rate of change is transferred to the microcontroller and applied to the system. The correctness of the outputs controlled by the software was confirmed by comparing them to the MATLAB simulation outputs.

3. Findings and discussion

Temperature control on the internal face of the helmet depends on the applied current. The PWM method is used to adjust the applied current. Figure 8 includes the PWM ratio-flow characteristics. The internal surface

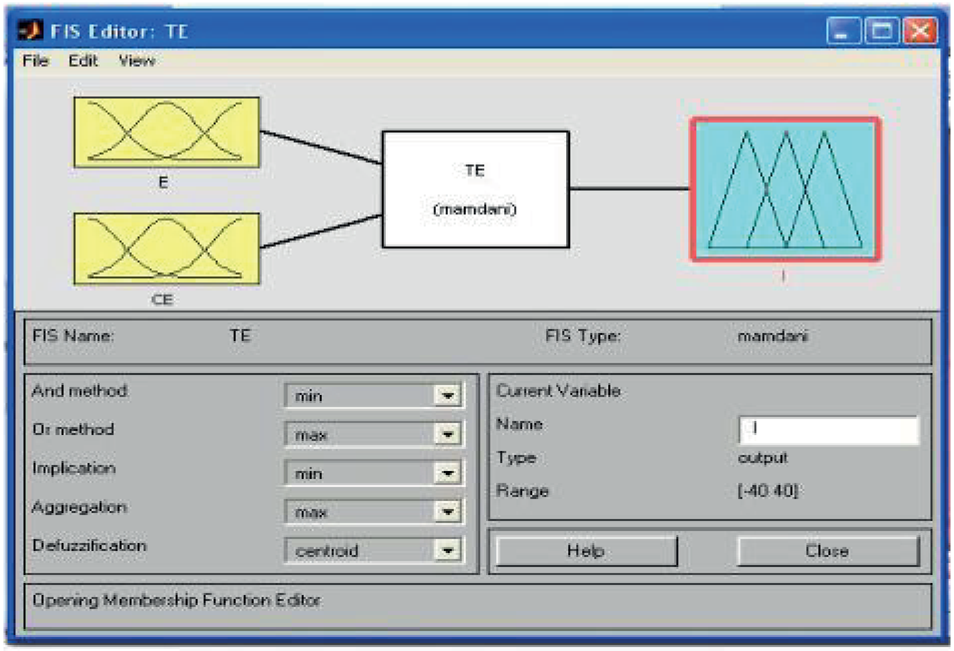

Figure 7. MATLAB fuzzy logic toolbox.

temperature of the thermoelectric helmet is the most important parameter. Figure 9 shows the internal surface temperatures for different current values. This graph shows that the maximum cooling performance is 37 A for the applied currents. According to the experimentally obtained scientific data shown here, the greatest temperature difference for the thermoelectric brain cooler occurs at 37 A and this temperature difference, ΔT, is 54 °C. The minimum temperature difference occurs when 5 A is applied and ΔT is 14.2 °C. The maximum current I_{max} of the thermoelectric helmet is seen at around 37 A according to the graphics in Figure 10. The currents applied at this point will reverse the ΔT-current curve. In this case, the I_{max} value has to be applied to the thermoelectric brain cooler to obtain maximum cooling performance.

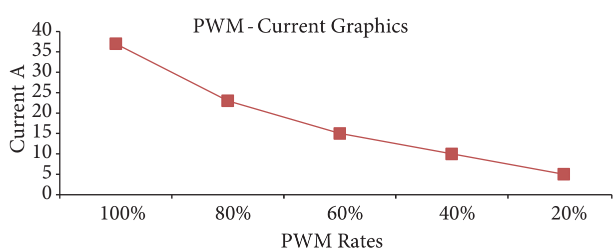

Figure 8. Current values for different pulse width modulation rates.

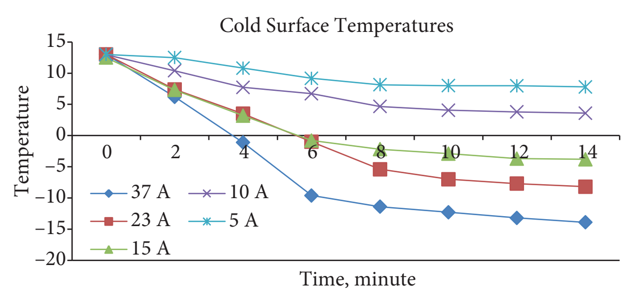

Figure 9. Internal surface temperatures according to applied currents.

When a module is exposed to an external thermal load, its performance varies. Figure 11 indicates the change of Q_C depending on different currents applied. Values in this graph were calculated by determining the heating forces that will make the ΔT value zero for each current. When the graph is examined, it is observed that the $Q_{C\max}$ value increases in accordance with the current. When the maximum current value is exceeded, the $Q_{C\max}$ curve is reversed. The $Q_{C\max}$ value also changes depending on T_H. When T_H = 15 °C at maximum current (37 A) the $Q_{C\max}$ value is 130.5 W, and when $T_H = 35$ °C the $Q_{C\max}$ value is 153 W. If the current drawn by the module $I \neq I_{\max}$, the Q_C value will give the potential cooling force of the helmet for any current I. The human brain emits heat at around 120 W. The thermoelectric helmet has the power capacity to cover this heat.

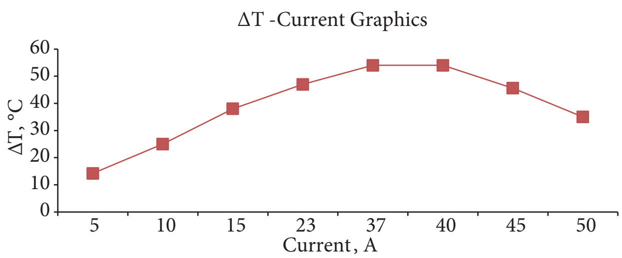

Figure 10. ΔT–Current graphics.

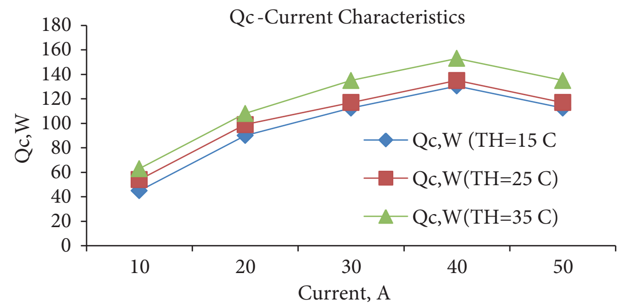

Figure 11. Q_c–Current characteristics of thermoelectric helmet.

Two issues need to be considered since the thermoelectric brain cooler will be used in patient treatment. When the helmet is placed on the head of the patient, the brain's internal temperature should not be less than 28 °C during hypothermia and the scalp should not be damaged. The maximum protective effect of hypothermia is known to occur when the brain's internal temperature is 30 °C. Scientific research and clinical applications show that human skin is not damaged when cooled down to –2 °C. Cold burns take place on the skin when it gets below this temperature. With these restrictions in mind, and despite there being no danger, the first test related to the operation of brain cooler was done for the –1 °C temperature value.

The second test was carried out for 30 °C. The temperature of the environment was recorded by a separate thermometer during measurements. Temperatures on the thermoelectric brain cooler were transferred to a computer and recorded by external measurement with a Fluke calibration device. Values were compared with the temperatures transferred to the computer. Temperature measurements were recorded every 10 s and possible errors were prevented by repeating each test 10 times. Figure 12 includes the measurement results in the first application when the thermoelectric brain cooler was adjusted to –1 °C.

Figure 13 includes the result of the application done for $T_C = 30$ °C to test that the control system can operate the helmet heating mode and keep it stable at a selected temperature.

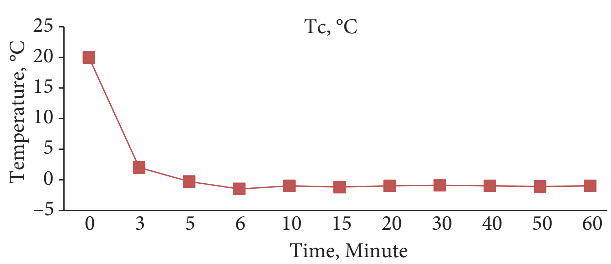

Figure 12. Temperature change graphics with –1 °C setup.

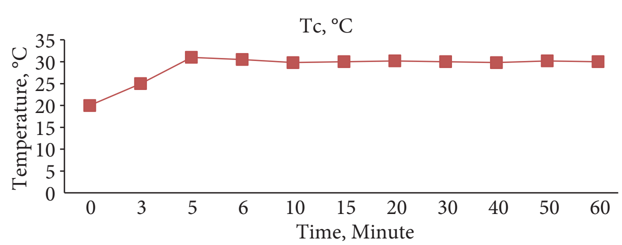

Figure 13. Temperature change graphics with 30 °C setup.

4. Conclusion

The thermoelectric brain cooler reaches the set temperature very quickly and can be kept stable at this temperature for a long time. Therefore, this technology is perfect to ensure brain hypothermia. This stability can be achieved regardless of whether the system is in cooling or heating mode. The internal surface temperature of the thermoelectric brain cooler can be reduced from 20 °C to –1 °C in 4 min and to 30 °C in 1 min. Test findings show that the control strategy applied is very convenient for the material used.

Based upon these findings, the average cooling capacity of the brain cooling system was measured as 153 W. Given that the temperature released from the brain is 120 W, it has capacity enough to cool the brain. The cooling speed of the system is 0.5 °C and can be adjusted by the software. Since this design can be used in transfer vehicles, is directly controllable electronically, does not include any cooling gas, and can work in heating and cooling mode stably for a long time, it can be utilized in protecting the brain.

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