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IoT-Based Brain Hypothermia System Using a Fuzzy Logic Controller and Measurements by Temperature Sensors

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Abstract

There is no doubt that hyperthermia can lead to permanent brain damage in patients. Several studies have shown that the use of devices to lower brain temperature reduces death rates. Here, a device for reducing brain temperature was designed and practically implemented. The device was mainly composed of Peltier cooling elements, a helmet made of plastic tubes with a suitable thermodynamic coefficient of heat absorption, cold water circulating inside the tubes (to cool the head), an Arduino Mega microcontroller, sensors for measuring the patient's temperature, and a NodeMCU ESP8266 Wi-Fi microcontroller (to analyze and display the temperature data). The patient's temperature data were then transferred via the Internet of Things (IoT) and displayed online on the Thing Speak website. Two water pumps were used, the flow rate of which was modulated using a fuzzy logic controller. The practical results showed a decrease in patient temperature to 36.5 °C within 12 min (traditional operation) and 8 min (fuzzy logic) using this device. The significance of the proposed device lies in its ability to lower brain temperature and mitigate the risk of permanent brain damage in patients. This was achieved by utilizing Peltier cooling elements, a helmet composed of plastic tubes with an appropriate thermodynamic coefficient (for efficient heat absorption), and cold water circulation (to cool the patient's head effectively). The effectiveness of the suggested method was confirmed by comparing the present results with those of previous studies.

Keywords: Arduino; fuzzy logic; helmet; hypothermia; Peltier; temperature sensor

Introduction

The rapid development of communications, especially wireless communications and communications to monitor the bio functions of patients, has resulted in changes in the treatment of several diseases, including stroke, heart disease, and hyperthermia [1, 2]. This development has led to an industrial revolution in electronics and artificial intelligence. Human brain hypothermia (HBH) is a crucial matter that has not been studied in depth because high temperatures degrade the condition of patients, as temperature is the main factor affecting the health and function of the human body [3, 4], as well as an essential vital sign [5]. Many researchers have devised solutions to the problem of high brain temperature by designing, manufacturing, and developing various devices that help reduce brain damage by cooling the brain [6] and allow the follow-up of the patient's condition, whether at home or in the hospital [7].

Thing Speak is a modern monitoring system that consists in a platform that provides services based exclusively on the Internet of Things (IoT) [8]. It is characterized by storing and displaying information and data on the system. The analysis and visualization of the data using MATLAB or other software are also possible. For the proposed system, a device was designed to reduce brain temperature by developing a head-cooling helmet with lightweight plastic tubes and good thermal conductivity to the skin. This system was fitted hierarchically to fit all head sizes. The helmet was cooled through a closed water cycle, with cold water being passed within the helmet. The method proposed in this paper represents a new device for reducing brain temperature in patients and was composed of an Arduino controller (for water temperature control), a helmet for cooling the head, sensors for measuring water temperature and patient temperature, Peltier cooling elements for water cooling, a DC power supply, a fan, a radiator (to eliminate the heat generated by the Peltier element and the device), and an liquid crystal display (LCD) screen (to display the temperature readings). Data on temperature, heart rate, oxygen, and the flow velocity of the cold and hot water pumps were analyzed, processed, and displayed by the NodeMCU and a Wi-Fi network, then submitted to a global system, to allow the treating physician to safely determine and monitor the patient's temperature from anywhere in the world. The system was characterized by the creation of a unique account and password for each patient, to prevent unauthorized access and knowledge of the patients' data [9–12].

The main advantage of this method over those proposed in other studies was its ability to mitigate the risk of permanent brain damage by specifically targeting brain cooling. By focusing on the brain, the proposed method may lead to fewer adverse effects and complications compared with whole-body cooling. Furthermore, it addressed the need to minimize the duration of the cooling process and explore the immediate and enduring benefits of temporary brain hypothermia. The significant features of the proposed method included its practical implementation, the integration of IoT technology for data transfer and online display, the use of Peltier cooling elements and a helmet with optimized thermodynamic properties, and the application of a fuzzy logic controller for flow-rate control. The novelty of the system lay in the rapid reduction of the brain's temperature, which can expedite the clinical implementation of therapeutic hypothermia and provide immediate benefits in experimental stroke cases. Based on fuzzy logic, the device effectively lowered the patient's temperature to 36.5 °C within 8 min.

The contributions of this study to the relevant fields can be summarized as follows:

1. A non-invasive brain hypothermia system was designed and implemented to continuously control and monitor the patient's temperature using Peltier elements, an Arduino microcontroller, and temperature sensors.

2. The patient's brain temperature was controlled based on a fuzzy logic controller.

3. The time required to lower the patient's temperature was significantly reduced compared with the state-of-the-art device.

4. The patient's brain temperature was monitored remotely through the IoT.

Related Works

Several brain hypothermia-inducing devices have been studied in the literature. Cojocaru et al. [13] designed a non-invasive brain hypothermia-inducing device that was used for the treatment of stroke and hypothermia. This device aimed to introduce an improved system for lowering the body temperature by installing Peltier elements inside a helmet based on thermal energy. This device consists of a helmet containing Peltier elements that absorb heat via an electric current on one side and transmit it to the other. The mechanism of the device involves the flow of water through a coolant to form a closed circuit powered by an electric pump. This circuit and its function cool the Peltier element's hot part. The cooling efficiency is directly affected by the temperature of the water provided by the circuit. When the water temperature drops, more heat is absorbed. The elements are mounted on an adjustable helmet that adapts to the size of the human head. The Peltier elements are distributed in the helmet, to ensure that the low temperatures do not affect brain cells. One of the advantages of this device is that it is lightweight and inexpensive; however, it is affected by the ambient temperature.

In turn, Hassan et al. [14] designed a system for measuring brain temperature. In this system, Peltier thermos cooling elements are used and installed within a helmet to serve as the cooling method. The heat from the hot part of the Peltiers is cooled by using circulating water, to provide a long operating time and system cooling. The device consists of a Peltier main cooling element, a temperature sensor (NTC) to collect patient temperature in four places, an Arduino controller to control the device’s work, and a Raspberry Pi for image and data processing. The temperature-reading accuracy depends on the value of the NTC resistance and its matching with the exact value of the known resistor, to create a voltage divider. Therefore, a 20-kΩ variable resistor was used to set its value to the desired resistance using a millimeter. The functioning device showed that the helmet is flexible, weighs approximately 1.275 kg, and is suitable for all ages. The water regime is maintained at a continuous cooling rate for 12–72 h.

Giuliani et al. [15] created a non-invasive device to control the brain’s temperature by manufacturing a cooling compressed collar with a flexible external element. To use this device, a cooling collar is placed on the patient’s neck, to reduce pressure and the temperature on the arterial tributaries leading to the patient’s brain. The goals of the device are to control the lowering of blood temperature through the arteries connected to the patient’s head. The device consists in a temperature-regulating collar which is attached for the specified cooling time. The device was first applied to a group of adult sheep because the animals’ skin is resistant to low temperatures and contains lanolin. The initial results in the sheep group revealed a similarity between the sheep’s body and neck temperatures and their brain temperatures over 100 min. The brain temperatures then decreased to 36.5 °C. The human body has an average temperature of 37.5 °C, whereas the average temperature of the experiment was between 35.5 and 37 °C. Notably, the device can lower the temperature by up to 5% (5 °C), to prevent local freezing. This device is lightweight, easy to carry, and attractive in terms of shape. It can be attached to any body area and used in hospitals and/or to treat fever. The disadvantages of the device are that it freezes at the exact location where the collar is attached, which leads to blood clotting.

Cattaneo et al. [16] developed a technique for cooling the blood in the brain using intravascular catheters, to treat acute stroke. The catheter placed a cooled saline solution inside the blood vessels to treat acute stroke and intravascular clots. The main goal of the blood-cooling technique is to speed up the removal of clots within the blood vessels. The experiment was performed on a group of sheep in which the cerebral artery was closed for some time, after which catheterization was performed through the nose using angiography. The results showed that the blood temperature within the vessels decreased by 1–3 °C/h after 3 h of catheter use. The use of catheters is safe and does not cause tissue damage. Duan et al. [17] studied blood cooling in patients with stroke and heart disease through catheterization, which involved the injection of a cold saline solution into a vein that transports blood to the brain. The study experimented with a group of mice in which the cerebral artery had been closed for some time, followed by the infusion of a cooling solution into the artery. The results showed that the solution quickly passed into the vein and cooled the blood significantly, because the temperature dropped to 34 °C after 60 min. This study showed that the described method of catheterization of blood vessels is a rapid and inexpensive approach for reducing body temperature. This method is used in surgical operations to rapidly reduce the body temperature.

Seyedsaadat et al. [18] studied the selective cooling of the brain and rapid hypothermia employing the Neuro Save system, which involves the infusion of a cold saline solution into the esophagus. The system consists of essential components related to the patient and can be easily disposed of. It includes tubes, a fluid reservoir, two filters, and a heat exchanger. This system afforded a brain temperature reduction of 3 °C within 15 min. The advantage of this system is its ability to achieve a rapid decrease in temperature. However, several challenges remain, including the effect of a rapid temperature drop on the arteries connected to the heart. Zambrano-Becerra et al. [19] designed a helmet to cool the head, which aimed to reduce the head’s temperature by circulating cold air inside the helmet using Peltier elements. The helmet consists of Peltier elements, a battery, a heat sink, and a fan to circulate the air inside the helmet. The practical results of this helmet showed good efficiency and a temperature decrease of 2 °C/h. The device is lightweight, easy to carry, and relatively inexpensive.

Moreover, Mazalan et al. [20] designed a well-known commercial helmet composed of polyester. Its purpose is to cool the head and reduce the brain's temperature. In this system, the head is covered from front to back, for cooling. The helmet consists of holes that are filled with a substance called crystal. Before the experiment, the helmet is soaked in water to activate the crystal substance until it becomes gel-like. It is kept at 15 °C for 4 h, then worn by the patient. One of the disadvantages of this helmet is that it yields good results when the head is shaved. The practical results revealed a 1 °C reduction in head temperature. Zambrano-Becerra et al. [21] designed a portable, easy to use, helmet-based cooling system to cool the head. Its purpose is to reduce the temperature of the head and body in conditions of high temperatures. The helmet consists of Peltier elements and holes for ventilation, as well as heat exchange between the helmet and the Peltier element. The Peltier element was selected because it is lightweight and easy-to-use. The practical results of the helmet showed a clear decrease in head temperature. One of the disadvantages of this helmet is that it cools certain parts of the head, whereas the presence of openings and heat exchange cause discomfort to the person wearing the helmet.

Eldho et al. [22] also designed a helmet and jacket for cooling and lowering the body and head temperatures. This study aimed to reduce the temperature and control the heat in the outer perimeter. The jacket and helmet consist of Peltier elements and fans, whereas the heated part of the Peltier is cooled through the outer perimeter. The helmet and jacket are coated with an insulating material called polyethene, which facilitates heat distribution. These materials are considered minimal, and their cost is relatively inexpensive. The practical results were determined within a climatic environment where a temperature of 30 °C decreased to 22 °C when wearing the helmet and jacket.

Furthermore, Hu et al. [23] designed a cooling helmet dedicated to the head. The study aimed to design a cooling helmet suitable for workers and people. The helmet consists of a fan and PCM material that absorbs heat. The author tested three helmets: the first was normal, the second included a fan, and the third was covered with thermal absorption material (PCM). The experimental results obtained under high temperatures showed that the heat-absorbing helmet has the advantage of absorbing heat to achieve a cooling effect. The temperature within the helmet remained at 27 °C for 120 min. One of the disadvantages of the heat-absorbing helmet is that it does not perform well in terms of ventilation, because the scalp sweats and causes discomfort to the patient. The challenges inherent to these studies included the pumping of a cold saline solution, leading to a decrease in artery size, and the studies' lack of randomness, as the animals differed in weight and age.

Kim et al. [24] developed a novel method to lower the body temperature of newborn infants using an evaporation and heat-absorbing interaction. Their approach involved utilizing electronics, a pottery bowl as a heat and cold absorber, and sand and cold urea powder (to extract heat from the inside), to maintain the inner container at 17 °C for over 24 h. Moreover, the device included lamps to indicate high and low temperatures, making it user friendly for healthcare professionals. The experimental results demonstrated that the temperature of a piglet model placed in the bowl decreased to 33.5 °C at around 45 min, with an error rate of 1 °C. This solution is distinguished by its affordability and reduced electricity consumption compared with other devices. However, one of the challenges identified was the need for the presence of a nurse, to monitor the temperature fluctuations.

Cojocaru and Mardari [25] proposed the development of a device aimed at lowering and cooling the body temperature. They utilized Peltier elements and implemented a flexible control algorithm based on fuzzy logic to maintain a consistently low temperature. The primary objective of the device was to reduce the patient's body temperature. It comprised four Peltier elements, a thermostat for Peltier control, and temperature sensors. The system's behavior in regulating the patient's temperature was simulated by the MATLAB software. The findings demonstrated that the medical user could set a specific temperature through an interface. This interface also facilitated the visual monitoring of the patient's ear temperature during hypothermia. The Peltier element, which is known for its light weight, affordability, and high accuracy, finds applications in tumor treatment, prevention of chemotherapy-induced hair loss, and mitigating the risk of brain injury. It is compact and has a low weight, which renders it suitable for cooling food, control systems, and spacecraft. However, the efficiency of the Peltier element is impacted by ocean temperatures, posing a challenge in specific applications.

In their study, Cojocaru et al. [26] utilized the COMSOL multiphysics software to simulate the temperature distribution during hypothermia. The objective of their research was to enhance the functionality of the Peltier device to lower the body temperature. The COMSOL multiphysics program employed a three-dimensional model of four layers (scalp, bone, gray matter, and white matter) to simulate heat transfer to the brain. The program incorporated the specific characteristics of each layer. The primary aim of the research was to establish a medically safe approach for brain cooling. The study's findings demonstrated a significant reduction of brain temperature, ranging from 37 to 18°C, thus effectively achieving the desired outcome.

Kochanek and Jackson [27] suggested a therapeutic hypothermia (TH) system as being beneficial for stroke and brain cell death. However, some studies did not show the long-term advantages of TH in both adults and children. Concerns have been raised about the potential complications related to the use of TH in ischemic injury, including hemodynamic instability during the rewarming process, which could be detrimental to the brain. Researchers have proposed isolated brain cooling to achieve benefits without side effects in cases of brain injury. Target temperature management (TTM) has been introduced as a comprehensive approach for using TH and temperature regulation in critical care. In a significant study involving over 900 patients, the effects of 28 h of TH (33 °C) vs. a "normal temperature" (36 °C) were compared, yielding similar outcomes in both groups. Approximately 50% of patients experienced severe disability, coma, or death. These findings echoed those of the hypothermic groups included in successful cardiac arrest trials reported a decade ago. Consequently, TH and mild TTM have been recommended as treatment strategies for strict fever control in adult victims of cardiac arrest.

Kapıdere et al. [28] developed the HBH System to regulate the brain's temperature using a microcontroller. The HBHS comprises a helmet equipped with a control system. By employing the PIC16F877 device (8-bit microcontroller) and MATLAB software, the helmet's temperature was controlled within a range of 5–46 °C. The device offers a precision of ±0.5°C and utilizes a water circulation system. An advantage of this device is that it can be used during primary operations involving open-heart procedures, thus eliminating the need for artificial circulatory devices. Hypothermia induced by the device reduces brain swelling and mitigates other severe pathological consequences of hypoxia. The device is versatile and can be used in addition to conventional methods for hyperthermia and hypothermia. Integrating a microcontroller in the HBHS allows faster operation, reduced size, and improved usability. By effectively controlling the brain's temperature, the device offers numerous benefits for safeguarding against diseases. Conversely, hypothermia at a temperature of 33 °C proves advantageous in preventing further brain damage.

Imoto et al. [29] developed an innovative cooling system that utilizes thermoelectric Peltier element chips to lower the brain's temperature. The Peltier cooling element was linked to a heat sink through a water-circuit system, with two silicon tubes connecting to the heat sink. The water circuit operated at 37 °C and successfully decreased the temperature to 27 °C based on experiments conducted on adult male mice. The main advantage of this device is its efficient heat dissipation through water circulation, thus effectively countering the heat produced by the Peltier element. However, the system's significant challenge is the risk of tissue damage caused by the shallow temperature, reaching 60 °C.

Wakamatsu and Utsuki [30] developed an air-cooling system that utilizes a fuzzy logic control algorithm to lower the brain's temperature. The system comprises a mannequin with thermal properties that are appropriate to achieve decreased temperatures. It is designed to cool the brain effectively and offers the same level of precision as a cooling water system employing fuzzy control principles. The device has demonstrated high precision in controlling the brain temperature and exhibits significant potential for clinical applications. However, several challenges are associated with the device, including the enhancement of the control system equipment, the identification of an optimal algorithm, the mitigation of the dryness of the patient's skin resulting from evaporation, and addressing the issue of dryness caused by the evaporation process.

In their study, Cojocaru et al. [5] developed a surgical system that utilizes the Peltier element to reduce body temperature and decrease the risk of stroke. Those authors aimed to enhance the body-temperature-reduction system by incorporating Peltier elements into a helmet. The system consisted of four equally distributed Peltier elements placed on the patient's scalp and sensors to measure the temperature distribution between the head and the ear. The findings indicated that the device could lower the temperature by 3 °C. One notable advantage of this device is its versatility of application, which is attributed to the small size and even distribution of the Peltier elements. Furthermore, it can be used after surgery. However, the device faces challenges, such as leaving marks on the scalp caused by the intense cold generated during the cooling of specific areas.

Yavuz [6] developed a helmet to reduce brain temperature and minimize the brain cell damage caused by stroke. The helmet employs a control unit that utilizes fuzzy logic to assess its effectiveness in cooling brain cells. By applying an electric current ranging from 0 to 60 A, the helmet ensures that the internal brain temperature remains above 28 °C during hypothermia, to prevent harm to the scalp. The experiments determined the helmet's maximum cooling capacity to be 153 watts at various currents. A performance test was also conducted on the controller, recording data for 24 h, and showed that the helmet's inner surface temperature was between 2% and 30%. The significant advantages of this device include its ability to maintain a stable temperature over an extended period, its adaptability for use in vehicles and transportation, its direct electronic control, its absence of refrigerants, and its potential as an alternative method for reducing brain temperature because of its effective cooling performance and direct contact with the skin.

Based on the articles mentioned earlier, we can envision some challenges and limitations related to the manufacturing and development of a helmet designed to reduce temperature, as follows:

1. A rapid drop in brain temperature causes vascular shock and convulsions, which can cause death.

2. Because of exposure to severe cold, skin burns can result from direct contact between the cooling element and the skin.

3. The heavy weight of helmets. The helmets weighed up to 5 kg in some research works, which resulted in head pain among patients [5].

4. The helmet size is significant because of the presence of cooling elements, Peltiers, and fans within the helmet.

5. Long periods are required to reduce brain temperature (3 h in some cases).

Although the conventional technique used to achieve brain hypothermia can be beneficial in many cases, it also has several drawbacks and potential complications, as follows:

1. The conventional technique used for the induction of brain hypothermia often involves invasive procedures, such as inserting a catheter into the patient's blood vessels or using specialized cooling devices. These procedures carry their own risks, including infection, bleeding, or damage to blood vessels.

2. Brain hypothermia may not be suitable for all patients or medical conditions. It is typically recommended for specific cases, such as after cardiac arrest, traumatic brain injury, or neonatal hypoxic–ischemic encephalopathy. The effectiveness of brain hypothermia in other conditions may be limited or unknown.

3. Although brain hypothermia is intended to reduce the risk of brain damage, it can still have associated complications. Some potential risks include electrolyte imbalances, irregular heart rhythms, blood clotting abnormalities, and impaired immune function.

4. Although brain hypothermia can help protect the brain from further damage, it may also extend the recovery period for the patient. This treatment often requires an extended stay in the intensive care unit and can delay other necessary medical interventions or procedures.

5. Maintaining the desired target temperature during brain hypothermia can be challenging. It

requires close monitoring and the adjustment of cooling devices, which may lead to temperature fluctuations or inadequate cooling.

6. The conventional technique used for inducing brain hypothermia requires specialized equipment, resources, and expertise. Not all healthcare facilities have the necessary infrastructure or trained personnel to implement this treatment effectively, which limits its availability and accessibility.

7. Brain hypothermia can cause various side effects, such as shivering, increased blood pressure, changes in blood glucose levels, electrolyte imbalances, and infections. These side effects need to be carefully monitored and managed during the treatment.

Our proposed brain hypothermia system, which has been successfully implemented practically, differs from the other methods described in existing literature in terms of its simplicity in design, affordability, accessibility of electronic materials, user friendliness, and the speed at which it can reduce the patient's temperature to an average level of 36.5 °C using fuzzy logic within 8 min. Finally, the patient's temperature can be monitored remotely using the IoT, thus allowing continuous surveillance from any location at any time.

Problem Definition

The implementation of brain hypothermia systems can face several problems because of the extended target time that is required to reduce the patient's temperature. Extended cooling periods ranging from 24 to 48 h are often recommended to maximize the long-term benefits of TH [31]. However, this prolonged hypothermia can lead to a higher incidence of severe complications and patient discomfort. Moreover, prolonged cooling may increase the risk of infections, electrolyte imbalances, coagulopathies, and cardiovascular instability. Patients may experience shivering, which can be uncomfortable and interfere with the cooling process. Moreover, the longer duration of the treatment can increase the overall cost and resource requirements, making it challenging to implement on a wide scale. Therefore, minimizing the prolongation of the cooling duration while still achieving the desired therapeutic effects is necessary.

Materials and Methods

System design

Our proposed system consists of several essential parts: the helmet, Peltier's elements, a power supply (DC power supply), an Arduino, a water pump, a radiator, a fan, temperature sensors, insulation, relays, and a LCD monitor. Before initiating the mechanism of the device, the temperature of the water in the cold-water tank should be approximately 25 °C, after which the helmet and the temperature sensor are attached to the patient. The device's working duration depends on the patient's temperature (i.e., it functions until the desired temperature is reached). The device comprises two systems. The first system is used for the delivery of cold water to the helmet, whereas the second is dedicated to the cooling of the Peltier element. The device contains a cold-water tank and a pump that pushes cold water from the tank toward the helmet, while the water left in the helmet returns to the Peltier element system and the tank via a closed water cycle. Several sensors are placed to measure the water temperature inside the device, and a sensor is used to measure the patient's temperature. The sensors are distributed within the cold water tank as follows. The first sensor is placed inside the water pipe going into the helmet. The second sensor is positioned inside the water pipe from the helmet. The third sensor is located within the radiator's water pipe. The fourth sensor is fixed within the cold water. The final sensor is placed on the patient's body or head [27, 32]. A motor drive is connected to the cold and hot water pumps, to control the speed of the pumps' flow. A keyboard is connected to change the required temperature. Then, the system is connected via a Wi-Fi network using NodeMCU and displays the temperature data, heart rate, and oxygen on the global platform Thing Speak. Figure 1 presents the pipeline and instrument diagram used in the proposed design, whereas Fig. 2 depicts the system's electrical connections.

Here, we will briefly describe each of the elements included in our design:

1. Helmet design: The primary goal of the device's design was to cool the head, reach the desired temperature, and preserve brain cells. One of the

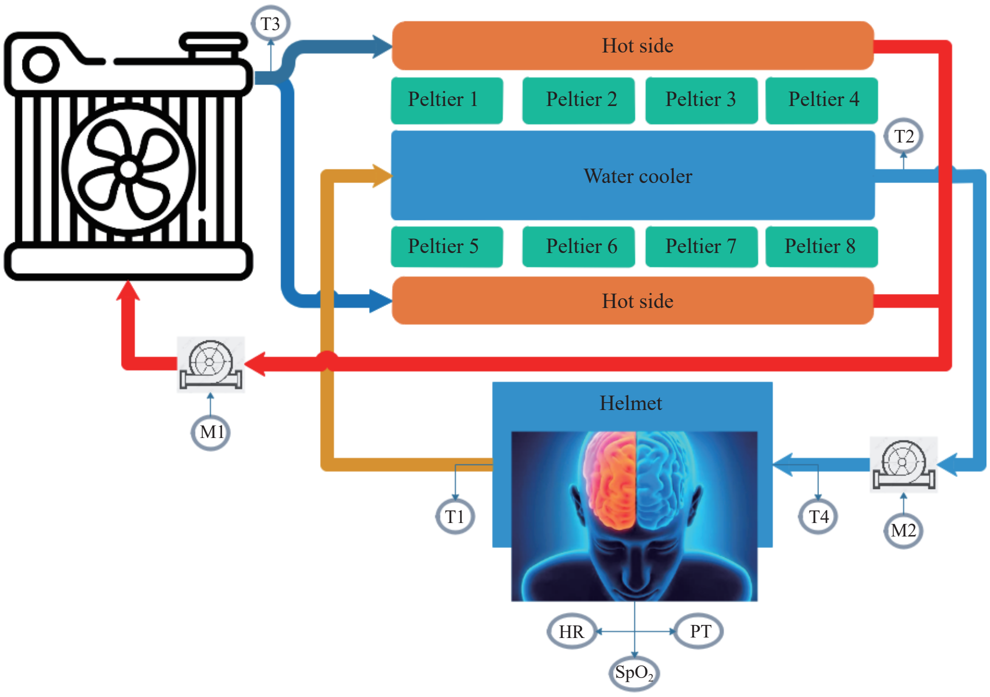


Fig. 1 Pipeline and instrument diagram of the study.

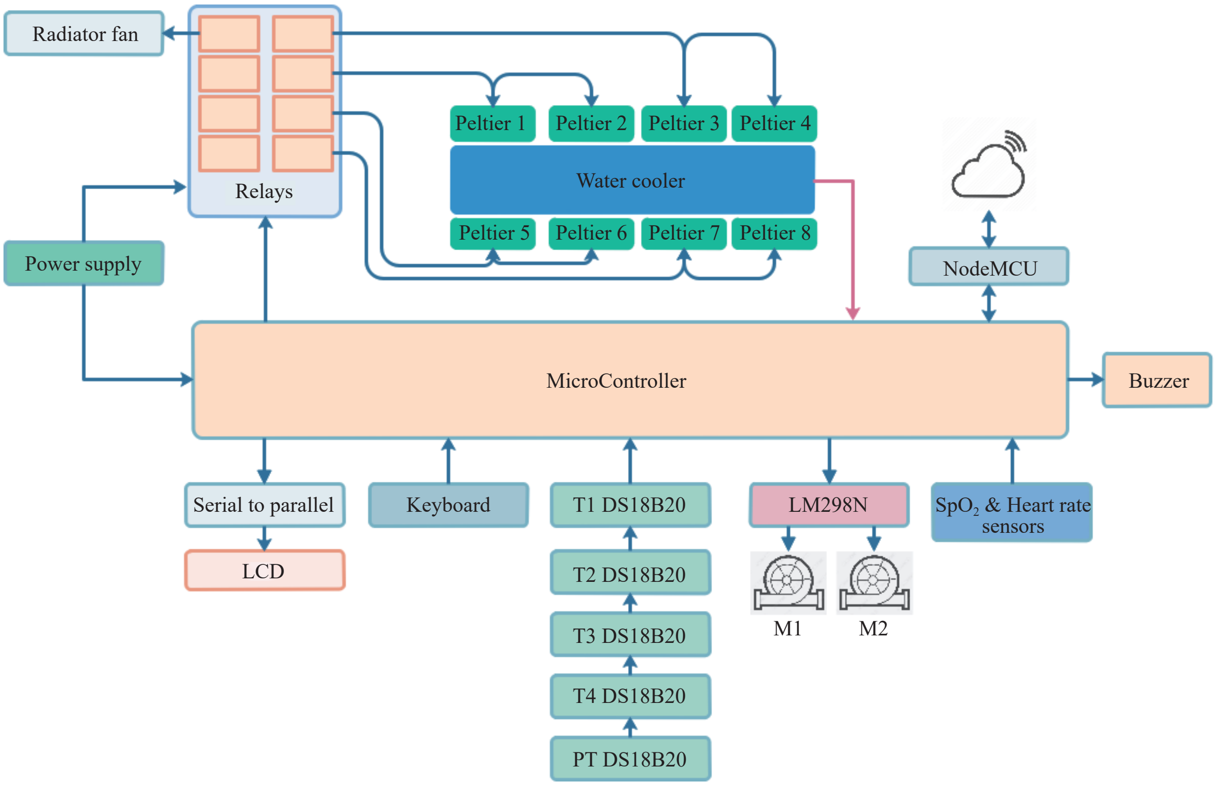


Fig. 2 Electrical connections of the proposed system.

components of the hypothermia device was the helmet, which was manufactured hierarchically by wrapping the plastic tube on the mechanics to adopt the shape of the patient's head. Two entrances to the helmet were included, i.e., an inlet for the entry of cold water and an outlet for hot water and its return to the device. The helmet tubes were designed in a plastic shape and were lightweight, to facilitate their wearing by patients of all head sizes. Cold water passed inside the tubes to cool the head. A sensor was placed within the helmet to measure the temperature of the water entering the helmet and the temperature of the water leaving the helmet [5, 13, 33, 34].

2. Peltier cooling: A Peltier element is a device that converts electrical energy into heat energy [35]. It includes two sides: one is hot and the other is cold. The unit worked as a heat pump, transferring heat from the cool side to the hot side. The device connected eight units in a series connection method, to reduce the current draw [36, 37]. A closed water system was inserted, to continuously remove heat from the hot side, so that the device worked efficiently and correctly. The current draw of the single voltage of the voltaic was approximately 10 amperes, and it operated on 12 or 24 volts [35, 36, 38, 39].

3. Water block: This was composed of an alloy made of aluminum with a width of 40 mm, a length of 120 mm, and a thickness of 12 mm. It had two 9-mm outlets for the entrance of the coolant (i.e., water), which helped dissipate the heat generated by the hot part of the Peltier element.

4. Controller: The Arduino microcontroller was the system's central controller for processing the data sent by temperature sensors to the Arduino and converting them from a standard signal to a digital signal for output on the LCD. The operating voltage of the Arduino microcontroller was 5 volts [14].

5. Temperature sensors: Digital temperature sensors (DS18B20) were used to measured the water and patient temperatures. The cable was approximately 100-cm long and worked on 3 or 5 volts [8, 40–42].

6. SpO_2 sensor: A MAX30100 oximeter sensor (i.e., SpO_2 sensor) was used for fingertip blood oxygen and heart rate (HR) measurements. Knowledge of the blood oxygen level of a patient is essential for detecting diseases [43]. Notably, this measurement is used in many medical applications. The power consumption of this sensor was very low because it is used in medical monitoring devices. It worked on 1.8 and 3.3 V, with a low current used to provide energy. In the proposed system, the sensor was used to determine patient's oxygen rate and HR and to present the condition to the treating physician via the global system Thing Speak within the IoT connection, because there is a direct relationship between high temperature, respiratory rate, and increased HR in patients [44–46].

7. Relays: A relay is an electrical switch that is activated by an electrical signal that controls the operation of the device. In the proposed system, seven relays were used to control the operation of the Peltier's elements and other components. The power supply of these relays was 5 volts, and they were able to pass 10 amps through their contacts. Four of them were used to control the operation of the Peltier system, whereas the remaining elements were distributed as follows: the fifth relay was dedicated to the cold water pump, the sixth relay was dedicated to the hot water pump, and the seventh relay was dedicated to the fan [47].

8. Buzzer: An alarm headset issued an alarm sound when 5 volts were applied. The alarm was connected to the device. When the required temperature was reached in the patient, the alarm was set off. Moreover, when the device was initiated, the alarm was triggered [48].

9. LCD monitor: An LCD monitor displayed the measured water temperatures based on sensors placed in cold and hot water. It also displayed the patient's temperature [49].

10. Water pumps: A pumping system pumped cold water into the helmet and hot water into the radiator. This system was designed to prevent leakage, worked for extended operating periods, was small, was quiet during the operating period, raised water to 3 m, and had a flow rate of 240 L/h. There were two pumps in the system. The first was used to drive cold water to the helmet, whereas the second was used to drive hot water from the helmet to the tank, to cool it and return it to the helmet. The system worked on 12 volts and drained a current of 300 mA [50].

11. Motor driver: An L298N dual-power motor H–bridge was used to operate a pair of motors on a DC voltage. The motor driver was characterized by the ability to control the speed and direction of the motor through the Arduino and other controllers. It worked on a voltage of 5–35 V and a current of 2 amps [51]. The motor driver was connected to the cold and hot water pumps, to control the speed of the water flow that reached the helmet, to reduce the patient's temperature if it increased and the speed of the cold water motor was high. During the temperature reductions, the motor pump decreased the cold water flow [52, 53].

12. Radiator: The radiator was a water cooler made of aluminum that was designed in the form of tubes and aluminum strips to increase the cooling efficiency and life of the device. We used a large radiator (43 cm × 40 cm × 5 cm) as a water tank and simultaneously employed it to cool the Peltier's system, to dissipate heat and cool the hot side of the Peltier thermoelectric cooler [54].

13. Fan: The system cooling fan was an essential part of this device. The fan related to the radiator to draw and distribute air while eliminating the heat generated by the radiator and the device. The fan operated at 5 volts and a current of 1.72 amps. The fan was 40 cm in width and 35 cm in height.

14. Cold water tank: The cold water tank was a 2-L basin covered with heat-insulating material that was used to store cold water.

15. Insulation: The insulation included tubes wrapped with insulating hoses made of rubber, which prevented cold water loss during the operation, protected the device against heat of external sources, and kept the water cool for as long as possible.

16. Keyboard: A 4 × 4 keypad was used to input the required temperature values in the device. It had 16 keys on the board. The operating voltage was 12 V DC.

17. Power supply: The power source was a source of electrical energy for the device in which two devices were installed. These were equipped with mechanical parts that required 25 volts, a high current of 100 amp, and a capacity for electronic parts with multiple voltages of 12 and 5 volts and a current of 5 amps. The device worked on the primary electricity source (220 V).

Experimental configuration

During the test, the speed gear was tuned where the cold water pump and the hot water pump were connected to the gear motor, to control the speed of the water flow. Thus, when a patient's temperature rises, the velocity of the cold water entering the helmet should increase, and the velocity of the hot water flowing into the radiator system should increase, to cool the hot part of the Peltier element. When the temperature reached the desired level, the flow rate decreased. In the second test, we assessed the control of the water flow velocity in the system. We placed a bag of hot water at a temperature of 41 °C inside the phantom, depending on the patient's temperature. The temperature sensor was placed inside the hot water bag, to measure its temperature. The bag was placed inside the helmet, and the temperature results were checked. When a temperature increase was detected, the speed of the hot and cold water pumps increased, to cool the water inside the phantom. The time that was necessary to reduce the temperature was approximately 12 min, after which the flow velocity decreased when the temperature reached the required level. Figure 3 depicts the manner in which the experiment was conducted and displays the temperatures and engine speed on the device's display.

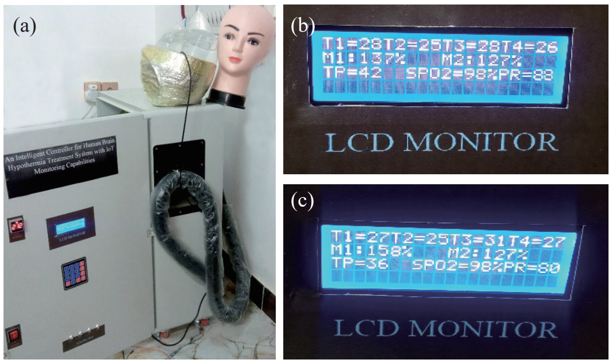


Fig. 3 Snapshot of **(a)** the experiment and (**b** and **c**) the display showing the temperatures, motor speed, HR, and oxygen percentage in cases of temperature increase and decrease.

Experimental configuration SpO_2

The HR and oxygen sensors were connected to the proposed system to determine the patient's HR and blood oxygen rate when their temperature increased. The power supply was connected to the Vcc with a capacity of 3 V, whereas the GND was connected to

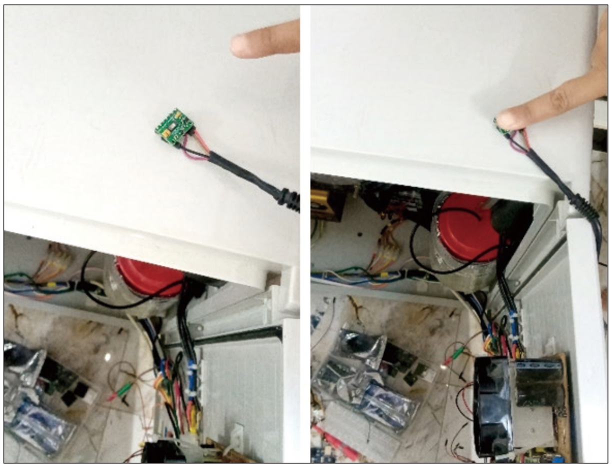


Fig. 4 Linking mechanism and placement of a finger on the sensor.

the Arduino GND, the serial data line (SDA) with the A4, and the serial clock line (SCL) with A5. Figure 4 presents the linking mechanism and placement of a finger on the sensor.

NodeMCU ESP8266

NodeMCU ESP8266 is an open-source program that is characterized by a high processing power and a large volume of data storage. It is also a precise control panel for the IoT regarding low processing capacity and data transfer to the server or the global system Thing Speak. It has advantages including a low cost and the ability to be used in several applications to connect to a local network or the Wi-Fi unit in our proposed system. NodeMCU was connected to the device, in which the board was programmed by Arduino Mega regarding the required values of temperature, HR measurement, oxygen, data storage, and processing for display, and then input into the Thing Speak system, where communication occurred via a protocol called HTTP [55–59].

Software framework

Patient temperature measurements from the DS18B20 sensor were obtained using the Arduino software. First, the Arduino program read the input temperature values. Then, the connection of the relays with the microcontroller was defined, as well as the LCD. The program code consisted of several libraries, including the Wire One library and the Dallas temperature library for temperature measurement (Fahrenheit or Celsius). Furthermore, they communicated the temperature data using the microcontroller. The LCD library was used to set up the LCD connection with the microcontroller. The I2C library was employed to enable the serial connection with the microcontroller. The role of the relay was to control the Peltiers by turn in it on or off. In the fuzzy control strategy, the cold water motor speed was not fixed; rather, it had a variable speed based on the temperature of the patient and of the cold water. The fuzzy controller measured the required speed and adjusted the motor speed via the motor driver. Simultaneously, the hot water pump speed was controlled based on the hot water temperature. Figure 5 presents a flowchart of the operation of the fuzzy controller.

Thing Speak initialization

The wireless communications and the communication to monitor patient functions have resulted in changes in the treatment of several diseases, including stroke, heart disease, and hyperthermia. The IoT is a global system that can be used to monitor the function of a patient and follow-up on their condition at home or in the hospital [7]. This functionality is critical in light of the spread of diseases and epidemics, including the coronavirus disease 2019. The Thing Speak program is a modern monitoring system that works as a platform that provides services [8] exclusively based on the IoT. It is characterized by storing and displaying information and data on the system. It is also possible to analyze and visualize patient data using MATLAB or other software. In the proposed

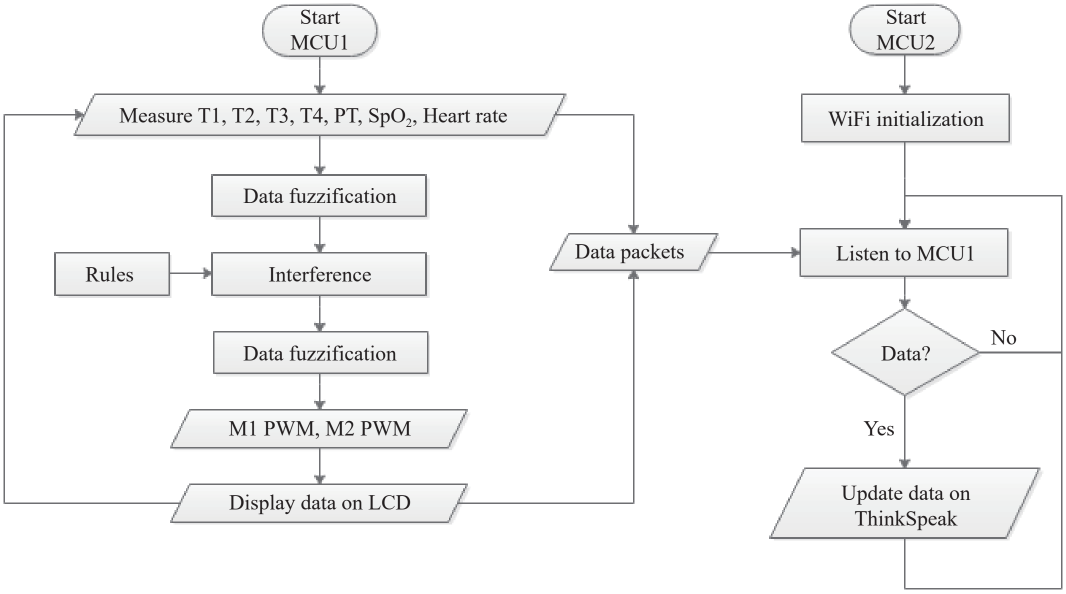


Fig. 5 Flowchart of the fuzzy control system.

system, data on temperature, HR, oxygen, and the flow velocity of the cold and hot water pumps were analyzed, processed, and displayed by the NodeMCU unit; moreover, a Wi-Fi network presented all data to the global system, so that a patient's temperature can be monitored by their treating doctor from anywhere in the world. This allows the treating doctors to safely follow-up on their patient's condition, because the system was characterized by the creation of a unique account and password for each patient [9–12]. Figure 6 depicts the Thing Speak connected to NodeMCU.

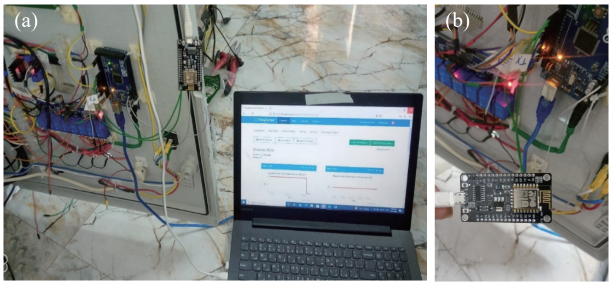


Fig. 6 NodeMCU node **(a)** shape **(b)** with Thing Speak.

Fuzzy logic design

Fuzzy logic is a mathematical control system that is used in artificial intelligence applications for data processing. However, Fuzzy is a sophisticated application that analyzes inaccurate analog input data (0, 1) because they cannot represent logical forms [60]. This modern system was introduced to develop the accuracy of sensors, such as control devices and temperature sensors, and improve their accuracy [61]. It is an easy approach to the analysis of body temperature. In the proposed device, the Fuzzy Library in Arduino Mega was used because it is an automatic control tool [6, 33, 47]. Figure 7(a) depicts the MATLAB fuzzy design structure. In this experiment, we added the fuzzy logic system with the drive motor to the cold water system, to increase the accuracy of the control of the patients' temperature by creating a MATLAB program consisting of two input parameters and one output parameter. Input-1 was the patient's temperature (PT), input-2 was the cold water temperature (Tank_T), and the output was the cold water flow rate (pump_motor). Its purpose was to control the speed of the cold water flow. As shown in Figs. 7(b) and 7(c), nine rules were implemented. These rules provided stability and accuracy to the patient temperature data. These possibilities were built in MATLAB. The input and output membership functions are shown in Figs. 7(d)–7(f). Equation (1) defines the triangular membership functions $\vartheta_A(x)$is, as follows [62]:

$$\vartheta_A(x)=\begin{cases} 0, x\le k \\ (x-k)/(l-k), k<x\le l \\ (x-m)/(l-m), l<x\le m \\ 0, x\ge m \end{cases}, \tag{1}$$

where the range k to m represents the extent of the support for the fuzzy set and l signifies the specific point within that range with the highest membership function value. Finally, the surface of the fuzzy rules is presented in Fig. 7(g).

Results and Discussion

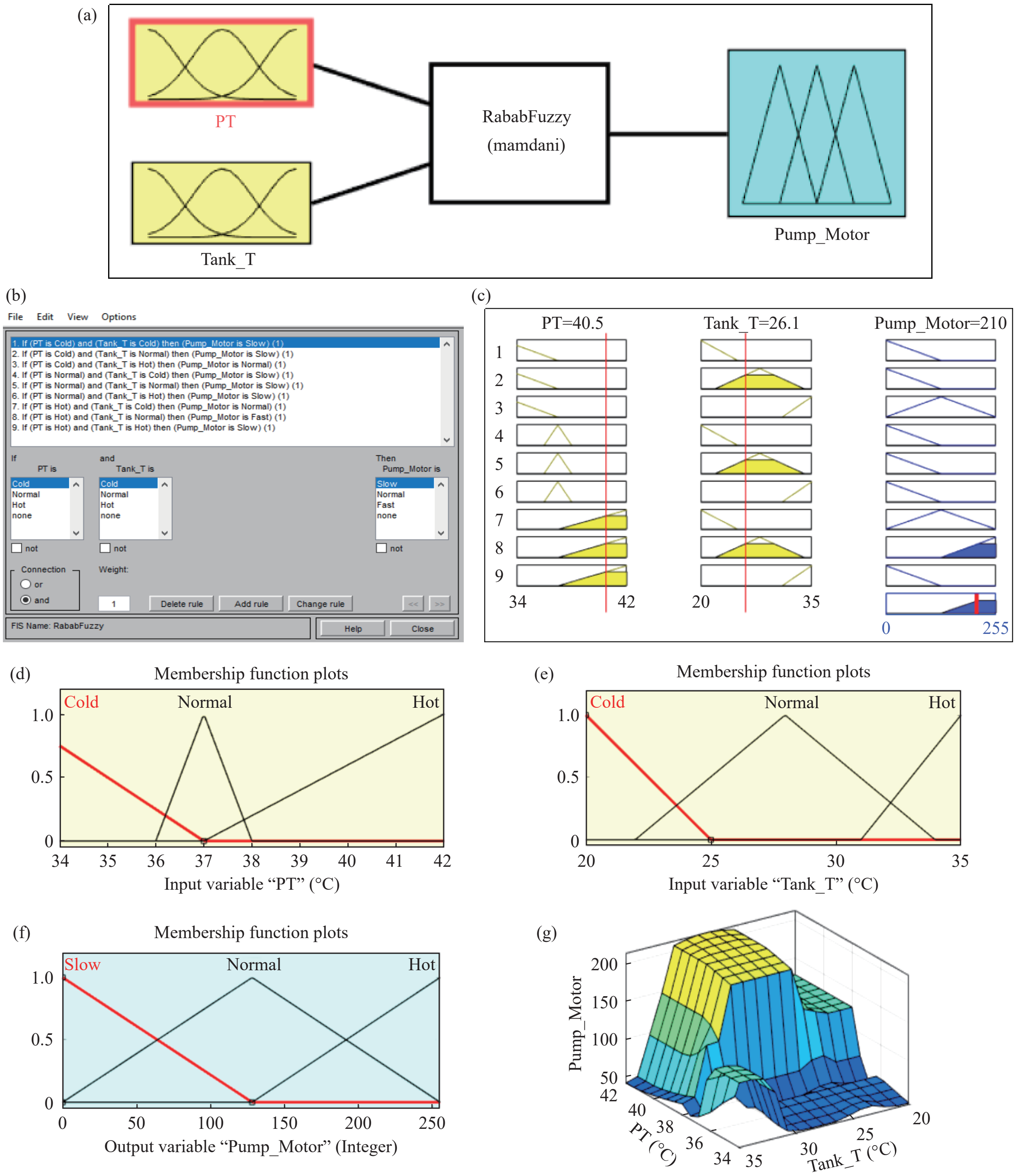
In this test, we connected the motors via the L298N motor drive, in which the cold water pump pumped the cold water from the tank to the helmet, and the hot water pump pumped the hot water from the Peltier heat exchanger into the radiator. The system controlled the speed of both pumps via a driver based on the control strategy.

Cold water measurement results

In this section, we present the results obtained through the utilization of traditional methods that involved employing on/off relays in response to changes in temperature. The outcomes of this approach are depicted in Figs. 8(a) and 8(b), which provided valuable insights into the system's behavior. Figure 8(a) showcases the temporal variation in the cold water temperature ($T2$). It demonstrates a significant decline in temperature, dropping from an initial value of 27–24 °C over 32 min. This rapid decrease underscored the effectiveness of the traditional method in achieving the desired cooling effect within a reasonably short time frame.

Figure 8(b) complements these findings by showcasing the relationship between the time and the pulse width modulation (PWM) of the pump's speed. The PWM level, as indicated on the y-axis, ranged between 205 and 54 throughout the 32-min interval. It is important to note that PWM controlled the power delivered to the pump, thereby regulating its speed. In this scenario, the PWM level dropped gradually as the cold water temperature decreased. This behavior aligns with Equation (2).

$$\mathrm{PWM}=T2\times\frac{255}{50} \tag{2}$$



1. If (PT is Cold) and (Tank_T is Cold) then (Pump_Motor is Slow) (1)
2. If (PT is Cold) and (Tank_T is Normal) then (Pump_Motor is Slow) (1)
3. If (PT is Cold) and (Tank_T is Hot) then (Pump_Motor is Normal) (1)
4. If (PT is Normal) and (Tank_T is Cold) then (Pump_Motor is Slow) (1)
5. If (PT is Normal) and (Tank_T is Normal) then (Pump_Motor is Slow) (1)
6. If (PT is Normal) and (Tank_T is Hot) then (Pump_Motor is Slow) (1)
7. If (PT is Hot) and (Tank_T is Cold) then (Pump_Motor is Normal) (1)
8. If (PT is Hot) and (Tank_T is Normal) then (Pump_Motor is Fast) (1)
9. If (PT is Hot) and (Tank_T is Hot) then (Pump_Motor is Slow) (1)

If PT is: Cold
and Tank_T is: Cold
Then Pump_Motor is: Slow
Connection: ○ or ● and
Weight: 1
FIS Name: RababFuzzy

Fig. 7 Fuzzy logic design, **(a)** MATLAB fuzzy design application, **(b)** fuzzy main rules, **(c)** rules viewer, **(d)** patient temperature input membership function, **(e)** cold water tank input membership function, **(f)** water pump PWM output membership function, and **(g)** rules surface

In Arduino code, the function analogWrite () uses an 8-bit resolution, which can generate 256 different output levels. When the value of 0 is used, the output will be off, whereas when a value of 255 is provided, the output will be entirely on. The values between 0 and 255 represent different levels of motor speed. A value of 50 in the denominator indicates the temperature level at which the controller ran the motor at full speed and abandoned its linearity.

Furthermore, the PWM level began its descent from 197 and dropped to 56 relatively rapidly, in line with the corresponding drop in cold water temperature. This trend indicates a strong correlation between the temperature and the PWM level, as the latter reacted proportionally to the changes in the former. The gradual decrease in PWM level continued until it reached the final value of 54, thus aligning with the target cold water temperature

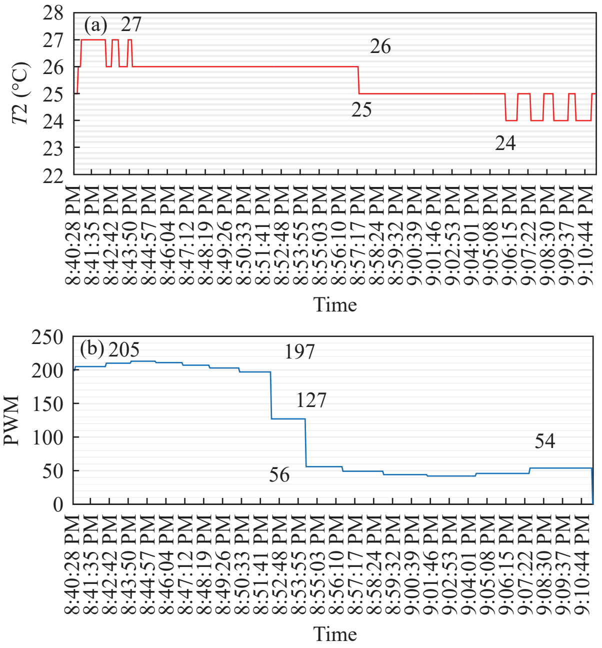


Fig. 8 Cold water (*T*2) **(a)** temperature and **(b)** pump speed (PWM)

attainment.

These results, which were obtained using the traditional method, provide valuable insights into the system's behavior and the efficacy of the on/off relays. The significant temperature drop and the corresponding PWM modulation observed here demonstrated the successful control and regulation of the cooling process. These findings highlight the potential of this method for achieving a precise temperature control and enable further analyses and comparisons with alternative approaches.

Hot water measurement results

This section presents the outcomes obtained using a conventional approach that employed on/off relays based on temperature measurements. The primary focus of this experiment was the evaluation of the effects of the hot water supply at the radiator system's inlet and the speed of the water flow within the system. The experimental setup involved monitoring various parameters and their interdependencies. Figure 9 illustrates the outcomes of these experiments. It demonstrates a clear relationship between the hot water temperature (*T*3) and the pump speed, directly affecting the heat-exchange process with the surrounding atmosphere. As depicted in Fig. 9(a), the temperature profile exhibited a staircase-like pattern, gradually increasing from an initial temperature of 27 °C to a final temperature of 31 °C. These temperature increments corresponded to the pump speed variations illustrated in Fig. 9(b). This observation highlights the dynamic nature of the system, in which changes in the hot water temperature prompted corresponding adjustments in the pump speed, to optimize the heat-exchange efficiency. Increasing the pump speed enhanced the system's capability to transfer heat to the surrounding environment, thus maintaining a desired temperature within the radiator system.

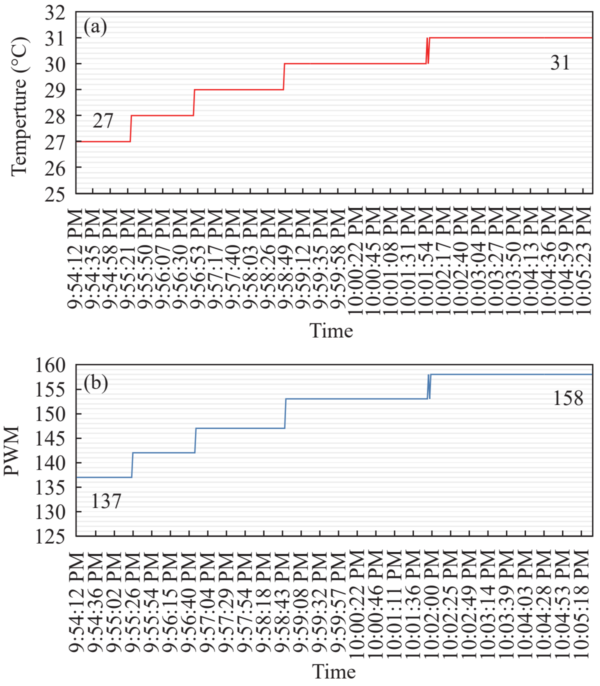


Fig. 9 Hot water (*T*3) **(a)** temperature, **(b)** pump speed (PWM).

These results provide valuable insights into the operation of the traditional system, showcasing its effectiveness in adapting to varying conditions. The correlation between the temperature and pump speed demonstrated the system's ability to regulate itself and ensure optimal heat exchange based on real-time conditions. However, it is worth noting that further investigations and comparative analyses are necessary to fully assess the system's performance and identify potential areas of improvement.

Patient temperature results

This experiment involved a temperature test of a simulated patient using a hot water bag. The water temperature used here was approximately 42 °C, representing the maximum temperature that a patient can reach before immediate intervention is necessary to prevent brain damage and potential fatality. The purpose of the experiment was to compare the effectiveness of the traditional system with that of the fuzzy logic control for managing patient temperature. Figure 10 in the research findings presents the results of the patient temperature test. Figure 10(a) illustrates the patient temperature based on the traditional method, whereas Fig. 10(b) displays the assessment of the patient's temperature using fuzzy logic control. The comparison between these two figures provides valuable insights into the performance of each approach.

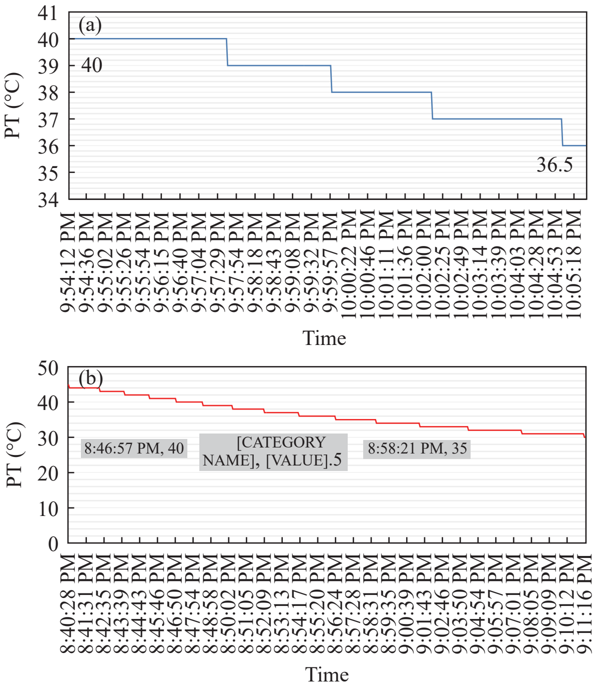


Fig. 10 Patient temperature results from **(a)** crisp logic and **(b)** fuzzy logic.

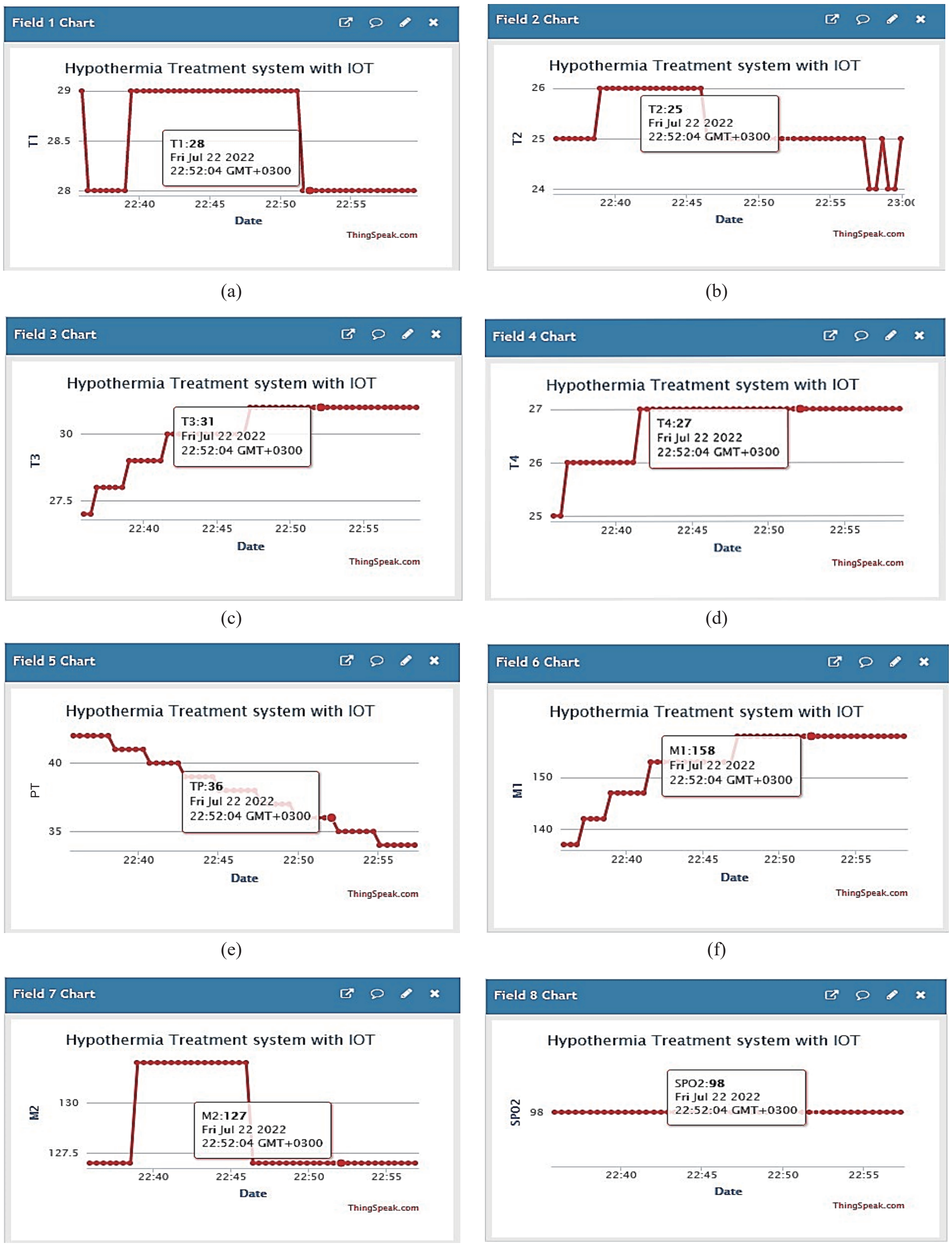
Figure 10(a) shows that the patient's temperature decreased in a staircase-like pattern from 40°C to 36.5 °C over 12 min. Conversely, Fig. 10(b) demonstrates a smoother temperature decrease, with the patient's temperature changing from 40 to 36.5 °C within a shorter interval of 8 min, because of the implementation of fuzzy logic control. It is important to note that the temperature achieved using the fuzzy logic control approach was lower than that achieved using the traditional method. The patient temperature attained using fuzzy logic control was 35 °C within a 12-min interval, which was 1.5 °C lower than that afforded by the traditional method. This suggests that fuzzy logic control can effectively reduce patient temperature and potentially mitigate the risks associated with high temperatures.

Furthermore, the results depicted in Figs. 10(a) and 10(b) provide additional insights. Based on these figures, it is worth mentioning that fuzzy logic control can yield a patient temperature as low as 30 °C. However, this lower temperature was attained at the expense of increased time. In contrast, the traditional method cannot decrease the patient's temperature beyond 36.5 °C. These findings indicate that fuzzy logic control offers advantages over the traditional method in achieving smoother temperature decreases within shorter intervals. It also has the potential to reach lower patient temperatures, although this comes with the trade-off of the increased time required for cooling. The ability of fuzzy logic control to regulate patient temperature more effectively could be valuable in critical situations in which prompt intervention is essential to prevent severe complications.

Recent research indicates that extended cooling periods ranging from 24 to 48 h may be crucial for maximizing the long-term advantages of TH [31]. Nevertheless, prolonged hypothermia can result in a higher occurrence of severe complications and patient discomfort [63]. In addition, focusing the cooling specifically on the brain might yield fewer adverse effects compared with cooling the entire body. Consequently, to expedite the clinical implementation of TH, it is essential to minimize the cooling duration and examine whether temporary brain hypothermia alone can provide immediate and enduring benefits in experimental stroke cases. Our proposed device addressed the concerns stated above by successfully reducing the brain temperature to 36.5 °C within a 12-min interval using traditional operation with on/off relays, as shown in Fig. 10(a). In contrast, when employing fuzzy logic control, the device achieved temperatures of 36.5 and 35 °C within time intervals of 8 and 12 min, respectively, as depicted in Fig. 10(b).

Thing Speak data presentation

In this section of the Results, all of the experimental data obtained from the proposed system were presented to the global system Thing Speak, with the temperature of the water entering the helmet being shown at $T1$. The cold water is shown at $T2$, the hot water in the radiator system is shown at $T3$, and the water coming out of the helmet is shown at $T4$. The cold water pump speed, hot water pump speed, HR sensor displays, and blood oxygen rate SpO_2 are also shown. Figure 11 presents the Thing Speak Online



(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 11 Thing Speak Online Channel data **(a)** $T1$, **(b)** $T2$, (c) $T3$, **(d)** $T4$, **(e)** PT, **(f)** $M1$ PWM, **(g)** $M2$ PWM, and **(h)** SpO_2.

Channel data: (a) $T1$, (b) $T2$, (c) $T3$, (d) $T4$, (e) PT, (f) $M1$ PWM, (g) $M2$ PWM, and (h) SpO_2.

Comparison Results

The proposed system was compared with the previous systems, which were analyzed regarding system configuration and resulted in extraction. It was found that the proposed system was characterized by easy access to the appropriate temperature in a short time, because a helmet with PVC pipes with an excellent heat coefficient was used to deliver the appropriate temperature reduction to the head. When the device was tested on a hot water bag at a high temperature of 42 °C (the highest a patient can endure), the hot water bag was placed inside the helmet. A decrease in the water temperature to the required level was observed without water freezing. Table 1 illustrates the comparison of the proposed method with previous

Table 1 Comparison of previous works for HBH with the proposed method

Ref./year	Adopted method	Sensor type	Sensor location	Temperature (°C)	Time to target Temperature (min)
[24]/2013	Evaporative cooling	Skin monitoring sensorRectal monitoring sensor	Abdomen	33.5	45
[25]/2014	Peltier cooling	Digital sensor temp (DS18B20)	Brain	19.2	N/A
[26]/2016	COMSOLmultiphysics	Peltier elements	Brain	27–33	300
[15]/2016	Flexible collar	Brain temperature sensor (PT-100 ATEX sensor)	Arteries of the neck	36.4	60
[6]/2016	Thermoelectric flexible thermoelements	Temperature sensor-based thermocouple	Brain	30	60
[17]/2016	Compact collar	Temperature sensors	Neck	36.5	100
[5]/2018	Peltier elements	Temperature sensors (NTC-10K-B3950)	Brain	15.8	N/A
[21]/2019	Intravascular catheters	Cold saline	Brain	34	60–90
[19]/2020	Intravascular catheters	Cold saline	Brain	35	60
[64]/2020	Superoxide dismutase and malondialdehyde kits	Cooling cap	Brain	28–30	4,320 (72 h)
[12]/2021	Peltier element, helmet	Temperature sensors	Brain	35	60
[18]/2021	Intravascular catheters	N/A	Brain	35	180
[65]/2021	Cooling machine	Temperature probe	Rectal	33.5	4,320 (72 h)
[66]/2022	Peltier Piping System	NTC temperature sensors	Brain	32	480 (8 h)
[67]/2022	Saline infusion	Temperature sensor (HEL-705-U-1-12-00)	Brain	32	14.2
[68]/2022	D-Brain cooling machine	Temperature sensor	Brain	32	2,880 (48 h)
[69]/2022	N/A	N/A	Brain	34–35.5	1,440 (24 h)
[70]/2022	Two bags of saline water	Thermometer	Rectum	33.5–34	180
[71]/2022	A Foley catheter inserted into the urinary bladder	Intravascular cooling device	N/A	32–34	1,440 (24 h)
[72]/2023	N/A	Temperature sensors (esophageal temperature)	Brain	33.5	360 (6 h)
[73]/2023	Alcohol and ice bags	Temperature probe (BAT-10)	Brain	34	15
[74]/2023	Cooling pad	Temperature probe	Brain	31–32	50
[75]/2023	N/A	N/A	Nasopharyngeal or esophageal	35.4	75
[76]/2023	Coil cooling units	Thermistor probe	Brain	30–32	1,440 (24 h)
This work	Helmet, water pipes,Peltier elements, Fuzzy logic control	Digital temperature sensors (DS18B20)	Brain	36.5 and 35	8 (for 36.5 °C) and 12 (35 °C)

relevant studies.

Conclusion

The proposed HBH device was successfully designed and implemented to reduce the brain's temperature effectively. The device utilized a helmet made of plastic tubes with good heat absorption properties, allowing for efficient cooling. Through testing with heat and cold water, we demonstrated that the device could gradually lower the patient's temperature to the desired level in approximately 8 min, utilizing fuzzy logic control to reach a stable temperature of 36.5 °C. The experiment's results suggest that fuzzy logic control shows promise in managing patient temperature and could potentially improve the outcomes in cases in which rapid temperature reduction is necessary.

The device achieved several important goals. First, it rapidly reduced the brain temperature to the required level. Second, the helmet's size was suitable for patients of all ages, and its lightweight construction (approximately 250 g) ensured minimal impact on the patient's head. The water flow inside the helmet was carefully controlled, ensuring safe and secure usage. The device also allowed the simultaneous monitoring of multiple patients, because of its ability to communicate information for more than one patient using the same device.

Furthermore, the device was portable and could be powered by a rechargeable battery, which enhanced its convenience and usability. Two additional sensors were incorporated to measure the heart rate and blood oxygen levels, to enhance patient monitoring and system performance. This enabled the device to provide valuable data on the patient's vital signs in relation to temperature changes. Moreover, the device was connected to an IoT system, for remote monitoring of a patient's condition anywhere in the world. This connectivity enhanced the device's usability and facilitated real-time data transmission for comprehensive patient care.

According to the results obtained in the current study, our work distinguished itself from the studies mentioned above in several ways. We incorporated three distinctive approaches: measurements of patient and water temperatures, implementation of fuzzy logic for patient temperature control, and the enabling of remote patient temperature monitoring through the IoT. In contrast, the previously mentioned methods either relied on traditional temperature-reduction techniques or could not remotely monitor the patient's temperature; alternatively, those studies were limited to one approach.

Further research and real-world implementation are required in future work to validate these findings and assess the overall effectiveness and safety of fuzzy logic control in clinical settings.

CRediT Author Statement

Rabab Talib Abdullah: Data curation, methodology, software, validation, resources, and writing–original draft. **Sadik Kamel Gharghan**: Conceptualization, investigation, methodology, project administration, supervision, visualization, formal analysis, writing–review, and editing. **Ahmed J. Abid**: Data curation, formal analysis, investigation, software, methodology, writing–review, and editing.

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Conflict of Interest

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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