AN EXPERIMENT TO ASSESS THE HEAT TRANSFER PERFORMANCE OF THERMOELECTRIC-DRIVEN CONDITIONED MATTRESS

by

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This study sets out to describe the design, construction and testing of thermoelectric-driven conditioned mattress intended to reduce the human-mattress interface temperature, in order to satisfy the personal sleep thermal comfort requirements in hot conditions. A prototype of thermoelectric-driven conditioned mattress is constructed and tested. A series of experimental studies related to the temperature of different cushion layers and time from start-up to stable state have been carried out, specifically to analyze the difference in heat transfer performance of two types of temperature control layers (i.e., integral water cushion and circulating water pipes) in cooling operations. The steady-state results showed that, the type of temperature control layer and pre-set temperature exhibited a remarkable influence on the cooling performance of mattress. The mattress with integral water cushion had a superior cooling performance as compared to mattress with circulating water pipes under similar conditions. Specifically, the upper surface temperature of mattress with integral water cushion at the pre-set temperature of 20 °C, 18 °C, and 16 °C were 1.97 °C, 2.46 °C, and 3.08 °C lower than indoor air temperature, respectively. Besides, the temperature contour maps of temperature control layer and upper cushion layer for two types of mattresses were constructed using the bilinear interpolation, respectively, thus expected to provide reference for the untested temperatures in this study. This study aims to effectively evaluate the heat transfer performance of the thermoelectric-driven conditioned mattress, and shows highly practical value in further applications of this system in improving human thermal comfort during sleep.

Key words*: mattress, thermoelectric cooling system, cooling performance, temperature contour map*

Instructions

Humans spend almost 90% of their lifetime indoors [1]. Sleep is essential to restore the body from physical and psychological and allow for the maintenance of optimal physical health [2, 3]. Mattresses are often used when people sleep. Previous research found that the sleeping on an adequate mattress has been observed to improve the sleep quality [4, 5]. The quality of a mattress depends on a number of characteristics including the adaptability to the body shape, the pressure distribution the human body [6, 7], or the ability to facilitate adequate thermoregulation [8, 9]. Among all of these, the latter exhibits the largest effect on the sleep quality perceived by the user [10].

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In terms of the thermoregulation, the current focus has moved to mattress manipulation [11, 12], regarded as a much more efficient approach. A number of strategies have been proposed including an electric heat blanket, or electrically heated sleeping bag [13, 14]. These powered temperature-controlled facilities may meet the human thermal requirements within the bed microclimate, but they are to some extent dangerous owing to the direct contact with the human body.

In this case, it would be important to develop a more suitable and flexible cooling/heating system for the mattress and assess its thermal performance adequately. Each type of the cooling/heating system differs in thermal performance and efficiency. As for the most optimal passive heat transfer devices manipulated by the cooling/heating system, the pipes with better thermal conductivity are widely applied in the household appliances thermal management [15], and its performance mainly depends on working fluid and operating conditions [16]. Several studies have reported that the pipes filled with water exhibits an excellent heat transfer performance [15, 17, 18]. This is related to the high latent heat of vaporization (2264.76 kJ/kg) and triple point temperature (–0.05 °C) of the water [16]. Moreover, the thermoelectric systems are mainly used to efficiently heat/cool the water filled with pipes. Significant research efforts have been made to design the water filled with pipes with improved performance [15, 19]. Wang *et al.* [15] assessed the thermal performance of loop PE-RT pipes filled with water as heat transfer device of a sleeping bed. It is believed that more heat can be transferred to the bed upper surface when the heat source is active. The pipe spacing and pipe water temperature have an obvious effect on the thermal performance, and the thermal performance of bed upper surface is effectively improved as a function of the water temperature. Xin *et al.* [20] explored application of a capillary radiation panel in the berth space in the train. The authors concluded that the water inlet temperature determined the final radiation panel temperature, and had a stronger effect on the human thermal comfort compared with the water flow rate. The reported methods have been successful in enhancing the heat transfer performance in heat mode, however, the development of the water filled pipes in cooling mode is stilled to be achieved.

Regarding the application of a cooling/heating system, some studied have investigated the temperature-controlled mattress. Rincon-Casado *et al.* [21] designed and constructed a prototype of thermoelectric-driven conditioned mattress, which includes a mattress and a thermoelectric system that cools the inner air and reduces the human-mattress interface temperature in hot conditions. Quesada *et al.* [11] designed a mattress with phase change materials to improve the heat dissipation of the human body during lying. Song *et al.* [22] developed a novel partial-body heating system, consisting of three electrically heating pads in the feet, buttocks and shoulder regions. In addition the above mattress in daily sleep, the heated mattresses have been designed to prevent core temperature reduction during ambulance or major surgery [19, 23].

From the aforementioned literature, no study to date has designed to analyze the thermal performance of applied water pipes or water cushion in mattress under hot conditions. Furthermore, the water filled in pipes manipulated by thermoelectric system exhibits potential advantages. Thus, an experimental study of thermoelectric-driven conditioned mattress is conducted in this paper, in which the integral water cushion and circulating water pipes are used as the temperature control layers inserted in the mattress. An experimental rig is built based on the sleeping thermal environment. The influence of pre-set water temperature and type of temperature control layer on the average surface temperature of different cushion layers of mattress in cooling operation are measured. Then, the mean temperature difference between different cushion layers and heat transfer performance for two types of temperature control layers under tested conditions are studied. Finally, the bilinear interpolation method was applied to construct the temperature map of different cushion layers. This study has potential to build a flexibly adjusted mattress for sleeping, and then improve human thermal comfort in hot condition.

Prototype of thermoelectric-driven conditioned mattress

The prototype is intended to provide thermal comfort to the user by adjusting the human-mattress interface temperature. To do so, a thermoelectric system cools mattress upper surface, which exchanges heat with the human body through that interface. Figure 1(a) displays the prototype of designed thermoelectric-driven conditioned mattress, which comprises a spring-structure mattress and an external thermostat, and the two are joined together through the hose wrapped with polyester foam.

The spring-structure mattress is displayed in fig. 1(a). It is 2000 mm × 1000 mm × 355 mm in size. Similar to a light flooring cooling system, the temperature control layer controlled by the thermostat is placed under the upper cushion layer. Two types of temperature control layer are chosen to conducted comparative experiment, including circulating silicone water pipes and integral silicone water cushion, as shown in fig. 1(b). The breathable upper cushion layer with a thickness of 25 mm is composed of a layer of soft 3-D fabric and polyester fabric, with the thermal conductivity of 0.0457 W/mK. The lower first and second cushion layer with total thickness of 80 mm are considered as higher thermal insulation, which are made of latex foam, with the thermal conductivity of 0.0363 W/mK. The pocket spring and polymeric sponge in proper order compose the rest of lower cushion layer.

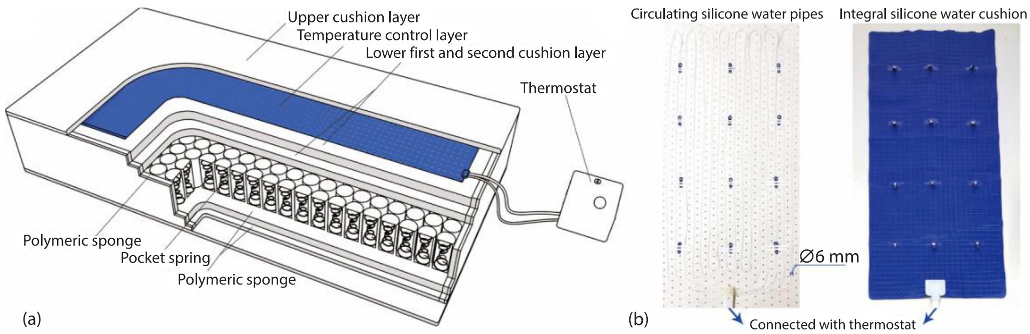

Figure 1. (a) Prototype of thermoelectric-driven conditioned mattress and (b) types of temperature control layer

The thermoelectric cooling system for the thermostat is presented in fig. 2, and composes four TEC1-12706 semiconductor refrigeration modules, specifically designed to work at indoor air temperature. Each module is 40 mm × 40 mm × 4 mm in size and presents a maximum input voltage of 12 V for a maximum electric power consumption of around 40 W. The modules are connected electrically in series to power supply and mounted between finned cooler sink (60 mm × 45 mm × 23 mm) and finned heat sink (100 mm × 100 mm × 33 mm). These sinks act as heat exchangers, essential in thermoelec-

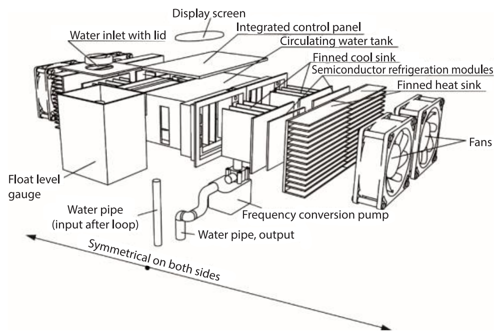

Figure 2. Sketch of thermoelectric cooling system for the thermostat

tric applications. Either sink is made of aluminum. The finned cooler sink is inserted a circulating water tank to cool water, while the finned heat sink is covered by a SUNON-100FZY axial fan that provides forced convection. An insulation layer separates the two adjacent heat sink to avoid thermal bridges. Besides, four NTC3950 sensors (one sensor per cool sink) and a float level gauge embedded in the water tank are used to test and record water temperature and water level, respectively. These are connected to an data acquisition system. The thermoelectric cooling system is used to cool circulating water to a pre-set temperature, and then the cooling water is injected into temperature control layer driven by a FS7341803H frequency conversion pump. The temperature range of thermostat is 14-29 °C.

The main source of the uncertainties includes the temperature measurement, and the current and the voltage measurements [21, 24]. The systematic uncertainty (the data acquisition device and thermocouples) is less than 2% in this study. The measurement error range associated with the systematic uncertainty is ±0.5 °C for each temperature sensor.

Experimental set-up

Heat transfer analysis

Figure 3 shows heat transfer forms between different cushion layers. The primary forms of heat transfer are forced to thermal conduction from temperature control layer to upper/lower cushion layer, and thermal convection and thermal radiation between the upper surface of mattress and room surface.

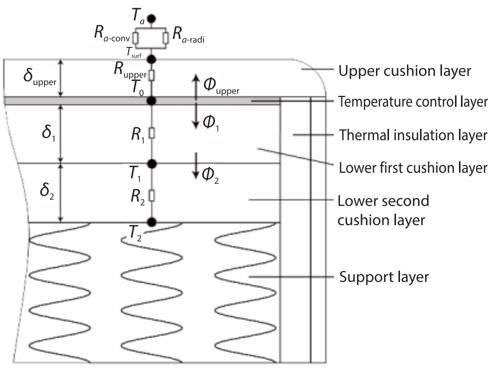

Figure 3. The heat transfer form between different cushion layers

In order to calculate the heat transfer performance between different cushion layers, the temperature is the temperature is selected as the evaluation index in this study. In fig. 3, T_a is the indoor air temperature, T_{surf} is the average upper surface temperature of mattress, T_0 is the average temperatures of temperature control layer, and T_1 and T_2 are the average temperatures of lower surface of first cushion layer and second cushion layer, respectively. For mattress with multilayer structure in fig. 3, the thermal resistance of each layer is calculated, eq. (1). The conductive heat flow to the surface of the upper/lower cushion layer is calculated, eq. (2):

$$R_i = \frac{\delta_i}{\lambda_i} \tag{1}$$

$$\Phi_i = \frac{A\left(T_i - T_0\right)}{R_i} \tag{2}$$

where R, δ, λ, and A are thermal resistance, thickness, thermal conductivity, and surface area of different cushion layers, respectively, and i represents numbers of the cushion layer.

Experimental set-up and procedure

Based on the heat transfer forms between each cushion layer, an experimental set-up was specially designed and constructed to evaluate the heat transfer performance from temperature control layer to upper cushion layer in cooling operation, with its scheme shown in fig. 4. The prototype is installed a climatic chamber that allows establishing steady values of indoor air temperature (27.0 ±0.3 °C), relative humidity (59 ±5%), and indoor air velocity (0.09 ±0.03 m/s). A thermostat can provide adequate thermoregulation and delivery cooling water with different temperatures for two types of temperature control layer. In the present study, six pre-set temperatures (*i.e.*, ST) of 16 °C (ST16), 18 °C (ST18), 20 °C (ST20), 22 °C (ST22), 24 °C (ST24), and 26 °C (ST26) are carried out.

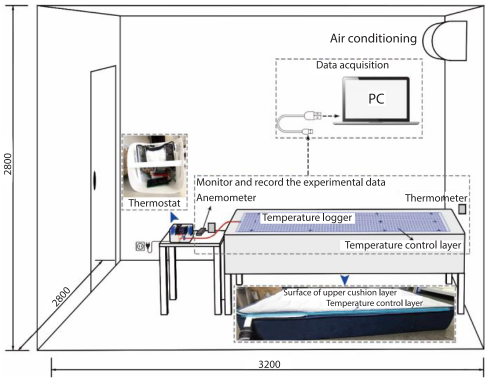

Figure 4. Scheme of the experimental set-up

To obtain reliable temperature data and cooling time from initial to stable state, the steady-state test procedure is standardized: adjust the indoor thermal conditions to desired steady values, inject the thermostat with water at 27 ±0.2 °C. Then, the thermostat is turned on and the corresponding pre-set temperature is set, indicating that the test begins. Finally, wait until the experimental time reach the assigned duration, and the temperature reach stationary values. Repeat the same procedures for the mattress at the other designated pre-set temperature. Each experiment is performed twice under the same operating conditions to ensure its accuracy and repeatability where the difference was controlled within 5%. Each experiment is conducted a total of 2.5 hours. During the experiment, indoor thermal conditions, temperature of each cushion layer and water temperature inside the thermostat are monitored and recorded for further analysis. The time interval between data collection is 1 minute.

Testing instruments

The iButton DS1922L (range: –40 °C to 85 °C, accuracy: ±0.5 °C) sensors measure the temperature at the upper surface (T_{surf}, 12 sensors), the temperature control layer, T_0, 12 sensors, the measuring sites of sensors are shown in fig. 1(b), the lower surface of first cushion layer (T_1, 12 sensors), and the lower surface of second cushion layer (T_2, 12 sensors). Moreover, the arrangement of measuring sites for other three cushion layers is the same as the temperature control layer. The TR-76Ui (temperature range: 0-45 °C, accuracy: ±0.5 °C. Humidity range: 10%-90%, accuracy: ±5%) self-recording data logger measure indoor air temperature (T_a, 2 data loggers) and relative humidity (2 data loggers), and these data loggers were placed at the bed head and bed end, respectively. The ZRQF-F30J (range: 0.05-30 m/s, accuracy: ±0.03 m/s) hot ball anemometer measure the indoor air velocity (V_a, 1 data logger).

Data analysis and statistics

To compare the temperature difference between different cushion layers for two types of mattresses, the processed data are:

– The mean values for each cushion layer are used to describe the temperature trend at the corresponding cushion layer affected by thermoelectric cooling system.
– The T_0-ST [°C]: the mean temperature difference between temperature control layer (*i.e.,* T_0) and pre-set temperature.
– The T_a-T_{surf} [°C]: the mean temperature difference between temperature control layer (*i.e.,* T_0) and upper surface (*i.e.,* T_{surf}).
– The T_{surf}-T_0, T_1-T_0, and T_2-T_0 [°C]: the mean temperature difference between T_0 and T_{surf}, between T_0 and T_1, and between T_0 and T_2 (symbols are shown in fig. 3).

Furthermore, the bilinear interpolation method will be adopted to construct the temperature contour map of the cushion layer and to predict the values of untested points, due to its simpler algorithms and operations. The contour map can be obtained fast through a three-step linear interpolation [25].

The schematic of the bilinear interpolation method is shown in fig. 5 where the co-ordinates (i, j), $(i, j + 1)$, $(i + 1, j + 1)$, stand for the locations of four known points, *i.e.*, a, b, c, and d. When a certain physical quantity, f, located at the unknown point P, *i.e.*, co-ordinates $(i + u, j + v)$ is predicted in terms of the quantities of four known points using the bilinear interpolation method, a three-step interpolation procedure is utilized and formulas are expressed.

First, the value of the unknown Points e $(i, j + v)$ and f $(i + 1, j + v)$ along the x-axis are calculated:

$$f(i, j+v) = (1-v) f(i, j) + v f(i, j+1) \tag{3}$$

$$f(i+1, j+v) = (1-v) f(i+1, j) + v f(i+1, j+1) \tag{4}$$

Second, the value of the unknown Point g $(i + u, j)$ along the y-axis is calculated:

$$f(i+u, j) = (1-u) f(i, j) + u f(i+1, j) \tag{5}$$

Finally, the values of the unknown Point P $(i + u, j + v)$ is calculated:

$$\begin{aligned} f(i+u, j+v) &= (1-u)(1-v) f(i, j) + (1-u) v f(i, j+1) + \\ &+ u(1-v) f(i+1, j) + uv f(i+1, j+1) \end{aligned} \tag{6}$$

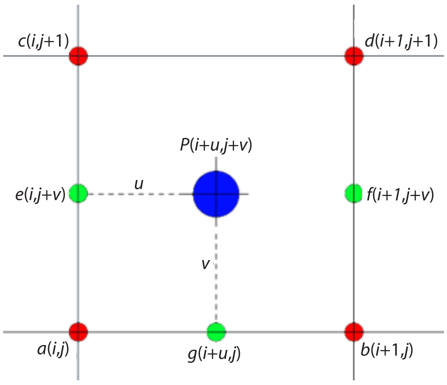

Figure 5. Schematics of bilinear interpolation method

where i, j are non-negative integers and u, v – are in the interval [0, 1). In these equations, v is the ratio of the distance between a (or b) and e (or f) to the distance between a (or b) and c (or d) and u is the ratio of the distance between a (or e) and g (or p) to the distance between a (or e) and b (or f).

Results and discussion

The heat transfer performance of mattress with integral silicone water cushion

The temperature distribution and mean temperatures at various points on the different cushion layers for various pre-set temperatures in cooling operation are shown in figs. 6-9.

As shown in fig. 6 and tab. 1, as for the temperature distribution of temperature control layer, the mean temperature in ST26, ST24, ST22, and ST20 decreased rapidly for 30 minutes after operation of the system and then tended to a steady-state, while the temperature in ST18 and ST16 attained the stable state after 40 minutes and 55 minutes, respectively. From the T_0-ST for all conditions in steady-state, the mean temperature differences ranged from 0.5-0.66 °C, which indicated the temperature of temperature control layer closed to pre-set temperature. Furthermore, when the pre-set temperature was decreased by 2 °C, the temperature of temperature control layer decreased approximately 2 °C. The aforementioned results mean that the temperature control layer has less heat loss when using the integral water cushion as a heat transfer device.

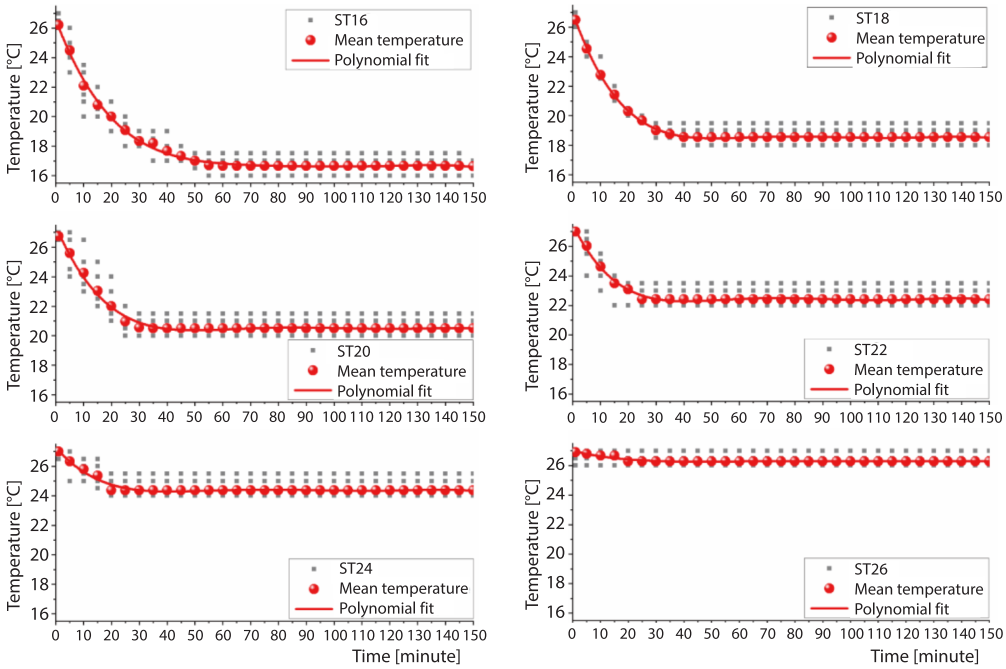

Figure 6. Temperature distributions of temperature control layer over time

Table 1. The time to steady-state and temperature different between different cushion layers

Conditions	Time to steady-state [minutes]	$T_0 - ST$ [°C]	$T_{surf} - T_0$ [°C]	$T_a - T_{surf}$ [°C]	$T_1 - T_0$ [°C]	$T_2 - T_0$ [°C]
ST16	55	0.66	7.25	3.08	6.59	7.84
ST18	40	0.54	6.00	2.46	5.21	6.43
ST20	30	0.58	4.45	1.97	3.67	4.87
ST22	25	0.51	2.97	1.51	2.49	3.37
ST24	18	0.50	1.58	0.92	1.25	1.83
ST26	10	0.50	0.07	0.43	0.05	0.28

In cooling operation, most of the heat could occur by thermal conduction from temperature control layer to upper surface. Figure 7 demonstrates that temperature of the upper surface is below the indoor ambient temperature for all the tests, and mean temperature is reduced by approximately 0.5 °C as the pre-set temperature is decreased by 2 °C. This result is mainly affected by temperature control layer governed by the thermoelectric cooling system. Figure 8 shows that the correlations between the upper surface temperature and temperature of temperature control layer in steady-state were obtained by the polynomial, and the relativities between fitted function and tested temperature was 0.9913. Furthermore, as shown in tab. 1, the $T_{surf} - T_0$ for all conditions mean that the heat loss of upper surface is comparatively large for all the tests except for ST26. This is because that the heat transfer is affected by the thermal resistance of the upper cushion layer and thermal convection between upper surface and room surfaces. In parallel, from the $T_a - T_{surf}$ in ST26, the minimum value of 0.43 °C was reached, whereas that for the ST20, ST18, and ST16 reached 1.97 °C, 2.46 °C, and 3.08 °C, respectively. It appears unlike-

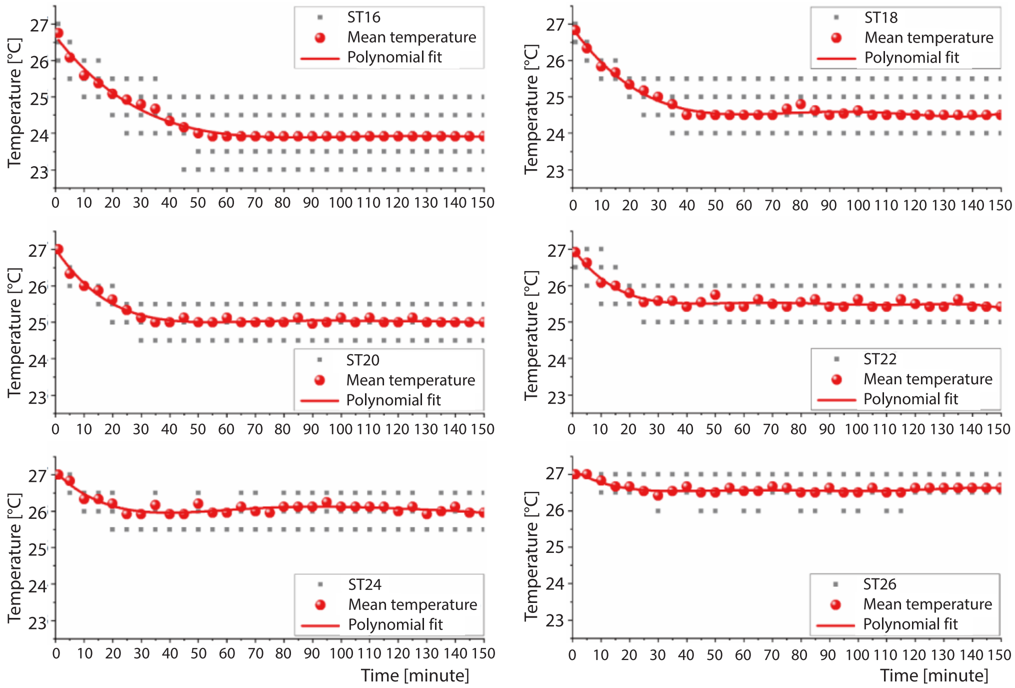

Figure 7. Upper surface temperature distributions of mattress in cooling operation

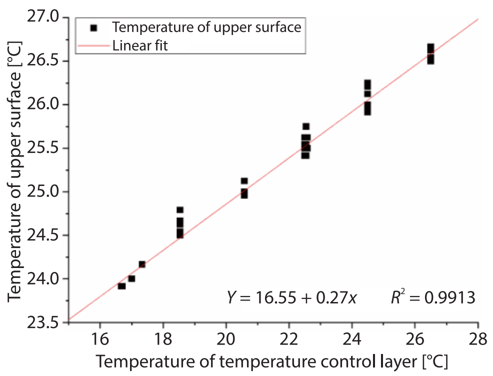

Figure 8. Positive associations between upper surface temperature and temperature of temperature control layer

ly that the pre-set temperature 26 °C may have positively affected the cooling performance of upper surface, whereas other pre-set temperature (*i.e.* ST20, ST18, and ST16) may have contributed largely. Also, Rincon-Casado *et al.* [21] derived at similar results based on the thermoelectric system to cool the upper surface by decreasing the inner air temperature of the mattress. These research results are expected, as the pre-set lower temperature renders the mattress a better cooling effect. Therefore, under these circumstances, the lying person is expected to increase the level of perceived thermal comfort at the human-mattress interface, compared to that provided by a non-conditioned mattress [10].

As presented in fig. 9 and tab. 1, the heat transfer from the temperature control layer to lower cushion layer also occurs in cooling operations. From the $T_1 - T_0$ and $T_2 - T_0$ for all conditions, it can be observed that the mean temperature differences are significantly increase as the thickness of lower cushion layer change from 40-80 mm. These differences indicate that the less cooling energy transfers downward through the lower second cushion layer. The main reason for these differences is the higher thermal resistance as the thickness of second cushion material increases. This result means that more cooling energy will change the direction of heat transfer and transfers upward through the upper cushion layer if the thermal resistance of the lower first cushion layer is increased, which makes the cooling system generally more efficient. Likewise, this conforms with the Fourier's law. This problem can be explored in future research.

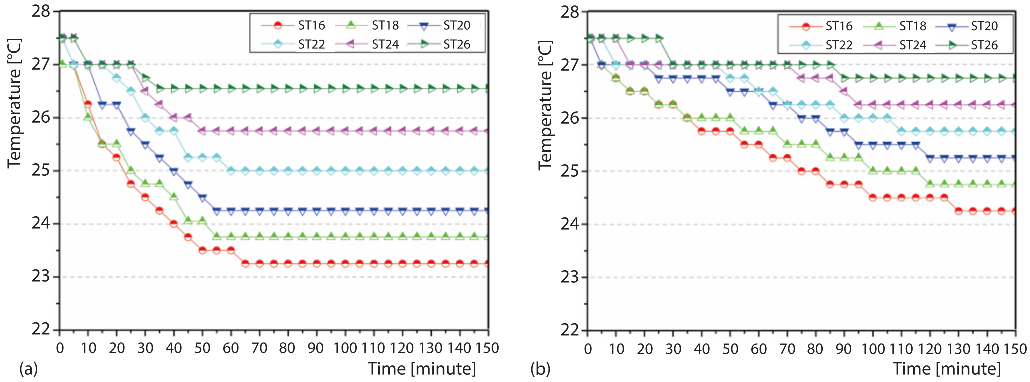

Figure 9. Mean temperature of lower cushion layers; (a) lower surface of lower first cushion layer and (b) lower surface of lower second cushion layer

The heat transfer performance of mattress with circulating silicone water pipes

The heat transfer performance of two cushion layers of mattress with circulating water pipes in cooling operation are shown in section *Appendix*, see figs. A1 and A2 and tab. A1).

Comparative analysis the cooling performance for two types of mattresses

As indicated in figs. 7 and A2, two types of temperature control layer controlled by the thermoelectric system are able to decrease the upper surface temperature below indoor air temperature, thus absorbing a significant amount of heat. This study demonstrates that the thermoelectric cooling system cannot only provide thermoregulation in cooling operation, but also has a better cooling performance. It also presents the maximum temperature difference attainable with the given temperature. The upper surface temperature is decreased by approximately 2.65 °C from ST26-ST16 for mattress with integral water cushion (*i.e.*, MWC), and it is decreased by 1.90 °C for mattress with circulating water pipes (*i.e.*, MWP). On the other hand, from the figures previously discussed and fig. 10, it can be observed that the upper surface temperature of MWC are lower than that of the MWP for all test conditions. Moreover, the lower the pre-set temperature, the larger the difference. With the same operating condition ST16, the upper surface temperature difference between MWC and MWP is approximately 1 °C. This difference is affected by the water pipe diameter and water pipe spacing distances (*i.e.* 30 mm). As a result, the integral water cushion has the better cooling performance and releases more energy into the upper cushion layer.

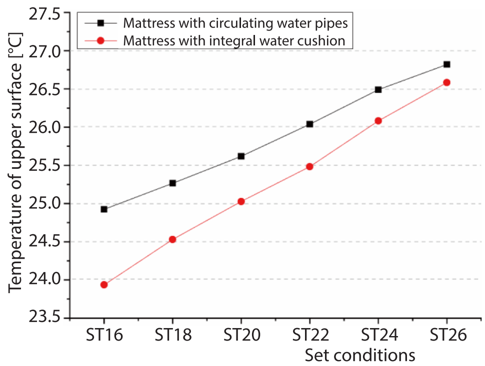

Figure 10. Comparison of upper surface temperature between two mattresses

Temperature map of different cushion layers for two types of mattresses

The designed thermoelectric cooling system can transform heat to cool the mattress upper surface. Furthermore, no matter what water pipes or a integral water cushion is considered as the temperature control layer, it works as a cool pump and absorbs more heat from different cushion layers of mattress, thus being more efficient than a simple waterbed mattress. In this case, it is necessary to structure the temperature contour map of different cushion layers, which can provide values reference for the development of mattress cooling system. This study attempted to integrate time and temperature dimensions, and assumed that the temperature process varied with the time and pre-set temperature. Thus, based on the tested temperatures in cooling operation, (see figs. 6 and 7, figs. A1 and A2), the temperature contour map of temperature control layer and upper surface are developed using bilinear interpolation for two types of mattresses, as shown in fig. 11. To verify the accuracy and validation of temperature map, the results obtained from the experiment and the interpolation method should be compared for two types of mattresses. From the temperature map, the interpolated results (IR) of the temperature control layer and upper surface could be obtained when pre-set temperatures were 17 °C (IR17), 21 °C (IR21) and 23 °C (IR23), respectively, see fig. 11. The same pre-set temperatures were also performed under same conditions. Figure 12 shows the comparisons of the interpolation results with the experimental results for three cases. The comparisons, which are made along with the whole trend and specific value in steady-state, indicate that the bilinear interpolation approach provides a result in a good agreement with experiment methods. In parallel, the results

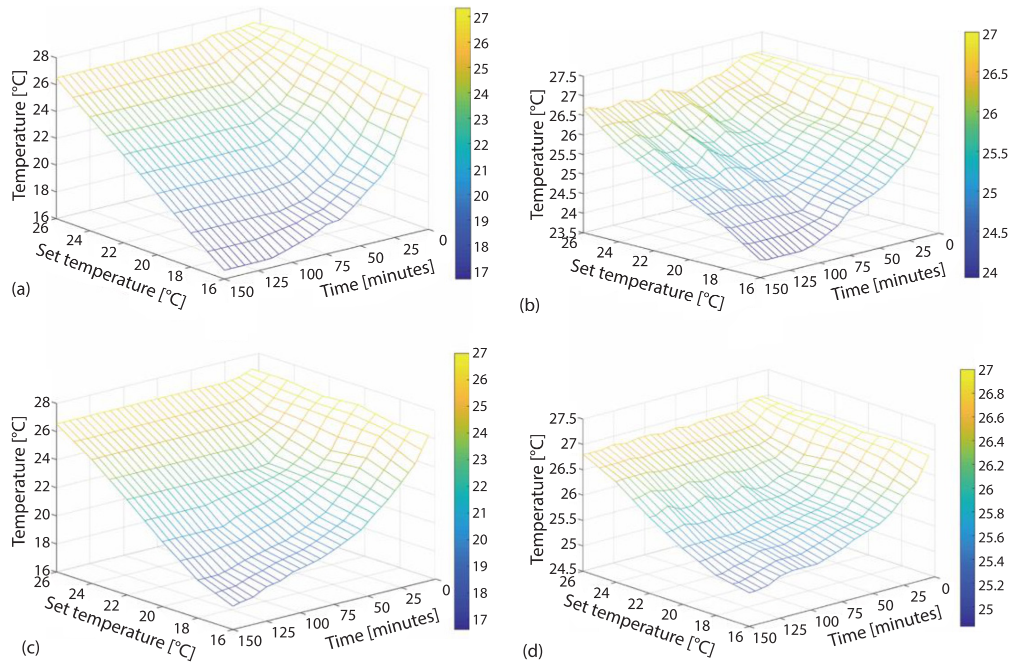

Figure 11. Temperature contour map for MWC and MWP; (a) temperature control layer of MWC, (b) upper surface of MWC, (c) temperature control layer of MWP, and (d) upper surface of MWP

of experiment and interpolation methods are compared using the root mean square deviation (RMSD). The relative errors are defined:

$$RMSD=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{X_{\text{interpolation},i}-X_{\exp,i}}{X_{\exp,i}}\right)^{2}} \tag{7}$$

The tab. 2 depicts that the errors between interpolation results and measured ones for MWC and MWP are less than 1%, which is an acceptable errors value in engineering applications [26, 27]. Thus, the interpolation method may be suggested as a good choice for its acceptable accuracy. Moreover, interpolation method could be used to calculate and predict the values of untested temperatures.

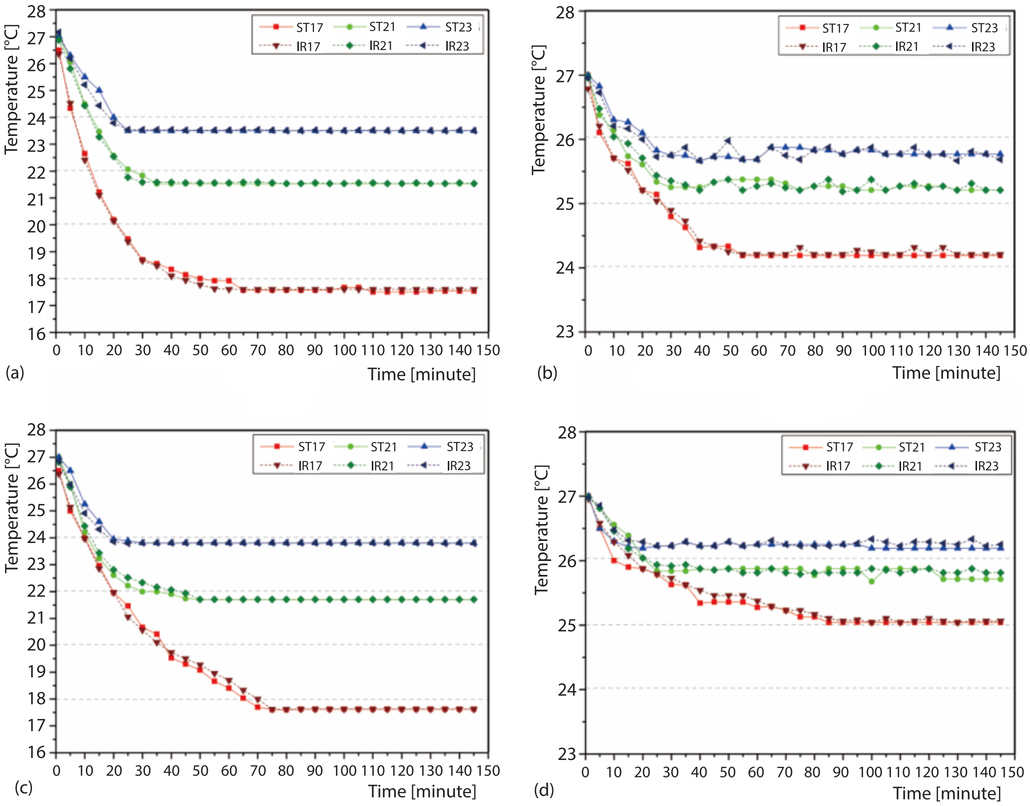

Figure 12. Comparison between the results of experiment and interpolation; (a) temperature control layer of MWC, (b) upper surface of MWC, (c) temperature control layer of MWP, and (d) upper surface of MWP

Table 2. Errors resulting from two methods in calculation of temperature of two cushion layers

Types	Temperature control layer			Upper surface		
	ST17	ST21	ST23	ST17	ST21	ST23
MWC	0.0072	0.0043	0.0051	0.0030	0.0032	0.0033
MWP	0.0083	0.0055	0.0050	0.0035	0.0033	0.0036

Conclusions

A Prototype of thermoelectric-driven conditioned mattress was designed and series of experiments were conducted. The following conclusions were drawn from this study are as folloows.

- The integral water cushion/circulating water pipes controlled by thermoelectric cooling system were taken as the temperature control layer for adjusting the upper surface temperature of mattress. It provides a new idea for the realization of applying the temperature control layer to improve human thermal comfort during sleep.
- The temperature control layer showed fast thermal response and efficient heat transfer performance in cooling operation. The temperature difference between T_0 and pre-set temperature ranged from 0.5-0.66 °C, indicating the temperature control layer had less heat loss. On the other hand, the most of the heat could occur by thermal conduction from temperature control layer to mattress upper surface. The mean upper surface temperature reduced by approximately 0.5 °C as the pre-set temperature decreased by 2 °C, and even lower than indoor air temperature from ST16 to ST26.
- The cooling performance of mattress with integral water cushion was superior to mattress with circulating water pipes under similar conditions, especially the better cooling performance under low pre-set temperature condition.
- The temperature contour map of the upper surface and the temperature control layer for two types of mattresses were developed using the bilinear interpolation, thus expected to provide reference for the untested temperatures in this study.

Appendix

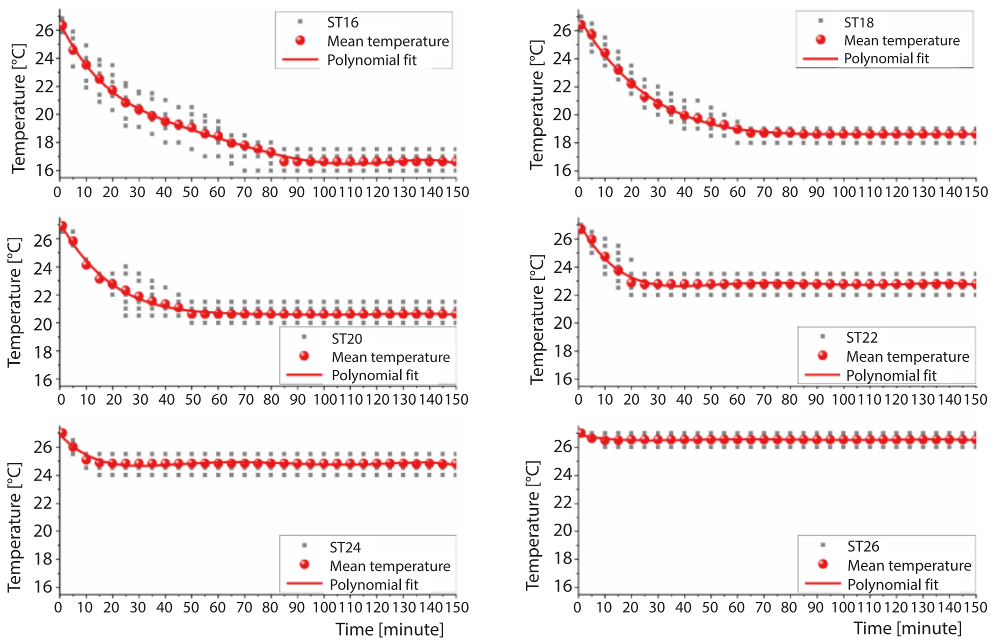

Figure A1. Temperature distributions of temperature control layer over time

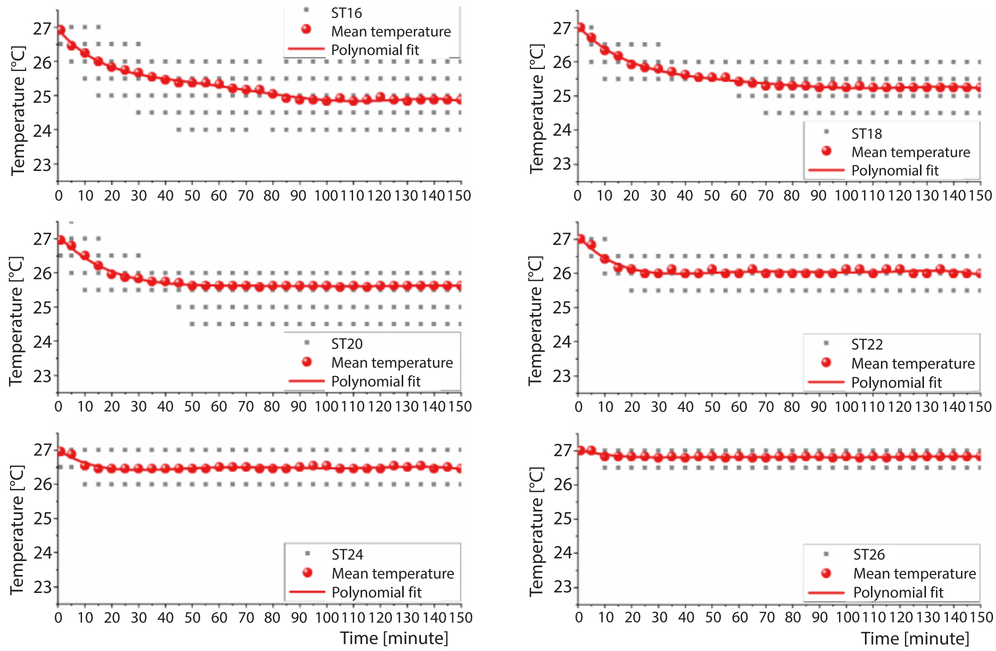

Figure A2. Upper surface temperature distributions of mattress in cooling operation

Table A1. Temperature difference between different cushion layers in steady-state

Conditions	T_0 – ST [°C]	T_{surf} – T_0 [°C]	T_a – T_{surf} [°C]	T_1 – T_0 [°C]	T_2 – T_0 [°C]
ST16	0. 67	8.22	2.11	7.61	8.78
ST18	0.64	6.63	1.74	6.11	7.00
ST20	0.63	4.99	1.38	4.63	5.26
ST22	0.79	3.25	0.96	2.96	3.46
ST24	0.78	1.66	0.51	1.42	1.92
ST26	0.54	0.28	0.18	0.21	0.46

Nomenclature

R – thermal resistance, [°CW^{-1}]
T_a – inoor air temperature, [°C]
T_{surf} – average upper surface temperature of mattress, [°C]
T_0 – average temperatures of temperature control layer, [°C]
T_1 – average temperatures of lower surface of the first cushion layer, [°C]
T_2 – average temperatures of lower surface of the second cushion layer, [°C]
V_a – indoor air velocity, [ms^{-1}]

Greek symbol

δ – thickness, [mm]
λ – thermal conductivity, [Wm^{-1}K^{-1}]
Φ – conductive heat flow, [W]

Subscripts

a-conv– thermal convection between mattress upper surface and indoor air
a-radi – thermal radiation between mattress upper surface and indoor air
i – numbers of the cushion layer

Acronyms

IR – interpolated results
MWC – mattress with integral water cushion
MWP – mattress with circulating water pipes
ST – pre-set temperature

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