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Artificial Neural Network, Experimental and Numerical Study on Air Cooling Rubber Mattresses for Elderly and Bedridden Patients

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Abstract

An artificial neural network (ANN) technique assesses the mattress temperature (body surface) of elderly and bedridden patients. The experimentally recorded body surface temperature data is used in the ANN analysis. The input parameters for the ANN model are sex, body mass index (BMI), room temperature, and cooling air temperature, while the output parameter is the body surface temperature. Many hidden numbers of ANN are trained to anticipate the parameter's optimal output. In addition, a numerical process is performed to consider the influence of room temperature by solving the governing equations for body surface and air temperature. ANN prediction errors for training and testing all datasets fall under the ±2.5% range. The numerical findings are compared to the measured data and the published results with 5.08% - 9.32% errors. The ANN findings were more accurate than the numerical model results. The current research employs the ANN technique for body surface temperature monitoring, effectively minimizing the risk of pressure sores in elderly and bedridden patients.

Keywords: Artificial neural network (ANN); Cooling systems; Mattresses; Numerical analysis; Elderly and bedridden patients.
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1. Introduction

Pressure ulcers (PUs) are one of the most prevalent issues in hospitals globally,[1] resulting in regional skin or tissue damage. Pressure ulcers are lesions that persist due to physical limitations.[2] Long-term compression of skin tissue reduces or stops microcirculation at a specific location. This causes ischemia and a shortage of oxygen in the tissues. Supraosseous pressure injuries are classified into three types based on tissue disruption: surface lesions, skin loss, and wounds of unknown depth.[3] PUs affect around 15% of patients and have grown by 63% recently. It has been estimated that 26%, 43%, and 39% of hospitalized patients, nursing homes, and spinal cord injuries,[4,5] respectively. Humans have a very effective thermoregulatory mechanism maintaining their core body temperature of about 37 ºC.[6] Humans are known as endotherms. Most heat produced by the body is regulated by metabolism.[7] The blood circulation transports the body's generated heat to maintain homeostasis. Without blood supply to the brain, the temperature rises to 73 °C.[8] As a result, blood flow is as important as metabolic heat generation, which usually falls between 36.5 and 37.5 ºC. Under normal conditions, body temperature is a significant factor in determining patient treatment.[9] Changes in average temperature suggest the possibility of organ malfunction and are a health concern for the patient.[10] Blood dispersion may produce changes in skin temperature at room temperature. These changes are the consequence of individual actions.[11]

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The temperature range for the PUs prevention is 30-36 ºC. As a result, certain mattresses may enhance pressure distribution in critical orthopedic areas. However, the high heat might induce pressure sores.[12] Infrared thermography was utilized to map the distribution of surface temperatures. It detects temperature fluctuations in the tissues and skin. It is commonly used for detecting early skin lesions.[11,13] People with PUs had an average skin temperature of 37.2°C, compared to 36.0 °C for those without.[14] Pressure ulcer therapy involves many techniques, including addressing the underlying issue (support surface and nutrition).[15] Different therapies, including dressings and topical care, have been developed to prevent and facilitate wound healing.[16-18] Weight loss and an inadequate diet increase the incidence of sores with pressure.[19,20] The recuperation is unpleasant and time-consuming-rehabilitative treatment while bedridden may assist in preventing such consequences.[21] As a result, this therapy aims to avoid future issues or alleviate current symptoms.[22]

Several studies have employed equipment such as compressed air beds, alternating pressure beds, cushions, and beds with a small quantity of air discharged to treat PUs. The therapy fully healed the wound.[23-25] Treating PUs in patients with customized air-compressed beds is more effective than normal hospital beds.[26,27] The therapy is comparable to alternating pressure mattresses and other support surfaces.[28–34] Wool and polymer foam were chosen as the optimal cushioning components for the mattress. The back, hips, and thigh temperatures were greater than in other areas. In comparison, the legs have the lowest temperature.[35] Heat discomfort is important for general health and sleep quality.[36] Several methods limit heat transmission from the body to the environment, including using bedspreads or blankets, thermally insulated bedding (sheets, blankets, duvets), and electric blankets.[37,38] The comfort level of a room is impacted by its surroundings.

Pressure sores in bedridden patients may be controlled and prevented by changing positions every two hours, monitoring the patient's movements, and adjusting the patient's body. A basic blood flow model has been developed based on bed surface temperature to lessen the pressure exerted on the body on bone protrusions caused by hard surfaces.[39,40] A bed with pressure sensors was created to detect and treat PUs in the elderly and to detect areas of maximum pressure.[41] Alarms will be sent to caregivers. An intelligent sensor with two balloon-like air cells is used in a mattress to monitor body pressure.[42-44] Another way to identify and monitor patients in bed is to match their body temperature to the bed's.[45]

Treatment should start to limit the death and disability. PUs may be monitored, prevented, and treated with control devices.[46] Several investigations have shown that water-filled pipes have high heat transmission efficiency.[47,48] In addition, much research has been performed to improve the efficiency of water-filled pipelines.[49] Under similar circumstances, air, water, and other cooling experiments have shown that mattresses with water-filled cushions outperform those with water-circulating tubes.[50,51] The performance, temperature management, and safety have all been investigated.[52,53] Bed air conditioning systems.[54,55] Direct heating/cooling air is delivered into the bed environment, and mattresses are heated/cooled with air or water.[56,57]. Furthermore, Internet of Things (IoT) technology is being utilized to monitor patient health. The system also includes a mobile application, which allows appropriate workers to monitor patients[58,59] remotely.

From the study of the literature mentioned above, it was found that there has been no study on the improvement or development of internal air circulation in air beds using an artificial neural network (ANN) analysis. The scope of this work is to apply an ANN technique for analyzing the mattress temperature (body surface) of elderly and bedridden patients. The experimentally recorded body surface temperature data is used in the ANN analysis. In addition, a numerical process is performed to consider the influence of room temperature by solving the governing equations for body surface and air temperature. The findings of this study may be used to assess the local heat exchange between the blanket covering the subject body and its surroundings, allowing for the progress of the subject bedding design with adequate thermal insulation.

2. Experimental facilities and procedure

The prototype attempts to adjust the mattress's temperature to give thermal comfort to the user in the test room at 5.00 m, 8.50 m, and 3.50 m. A thermo-electric air-cooling device was used to remove heat from the subject, as shown in Fig. 1. The experiment uses a 20.5 cm thick rubber mattress that is 90 cm wide and 198 cm long. Our rubber tubes are put into the rubber mattress along the bed, 2 cm below the surface (Fig. 1(B)). A fan forced cold air from the chamber into four rubber tubes at the head zone, which flowed to the opposite closed end (Fig. 1(A)). As seen in Fig. 1(C), thirty-four 5 mm diameter holes enable chilly air to exit the bed. The mattress surface temperatures (human skin temperatures) are measured using 18 type-T copper-constantan thermocouples with a 1 ºC uncertainty and a data logger (DT85) with a 0.01 percent accuracy (Table 1). Throughout the exposure, the individuals remained in their pajamas. They were instructed to avoid alcohol and caffeine-containing drinks before the experiment and to take it easy throughout the trial time. The measured

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process and some details are delivered to the volunteers before the start of the experiment.

The room temperature of 25, 30 ºC (40-50%RH) was chosen to correspond to the bedroom temperature discussed in the literature as well as the indoor environment needs and hospital patient rooms.[60-62] The experiment mode was activated for two hours at either a constant state or a lower temperature, with virtually all participants maintaining their arms beneath the blanket. To eliminate disparities in age, body type, and lifestyle, ten healthy Thai students—five men and five women—were chosen as participants. The subjects became accustomed to the bedding used in the experiment and maintained the same daily routine. All participants agreed and reviewed the fundamental research instructions, which outlined the goal of the surveys, how the experimental equipment operated, and what needed to be addressed. Conducting tests on bedridden or elderly patients without disturbing the other bedridden or elderly patients is challenging. Thus, the first study was conducted on healthy Thai students or other age groups. Assume the cooling system's operating conditions are adequate, including proper climate adjustment settings. In such a situation, installing specialized equipment or testing processes may be unnecessary since they have been fully evaluated on bedridden patients or the elderly, which will be the next stage in future research.

Table 1. Accuracy and uncertainty of measurements.

Instrument	Accuracy (%)	Uncertainly
Anemometer	0.1	±0.2
Dry-box temperature calibrator	0.1	±0.1
Data Taker& type T thermocouple	0.1	±0.1
DC voltage and current sensor	0.1	±0.01
AC digital power energy meter	0.1	±0.01

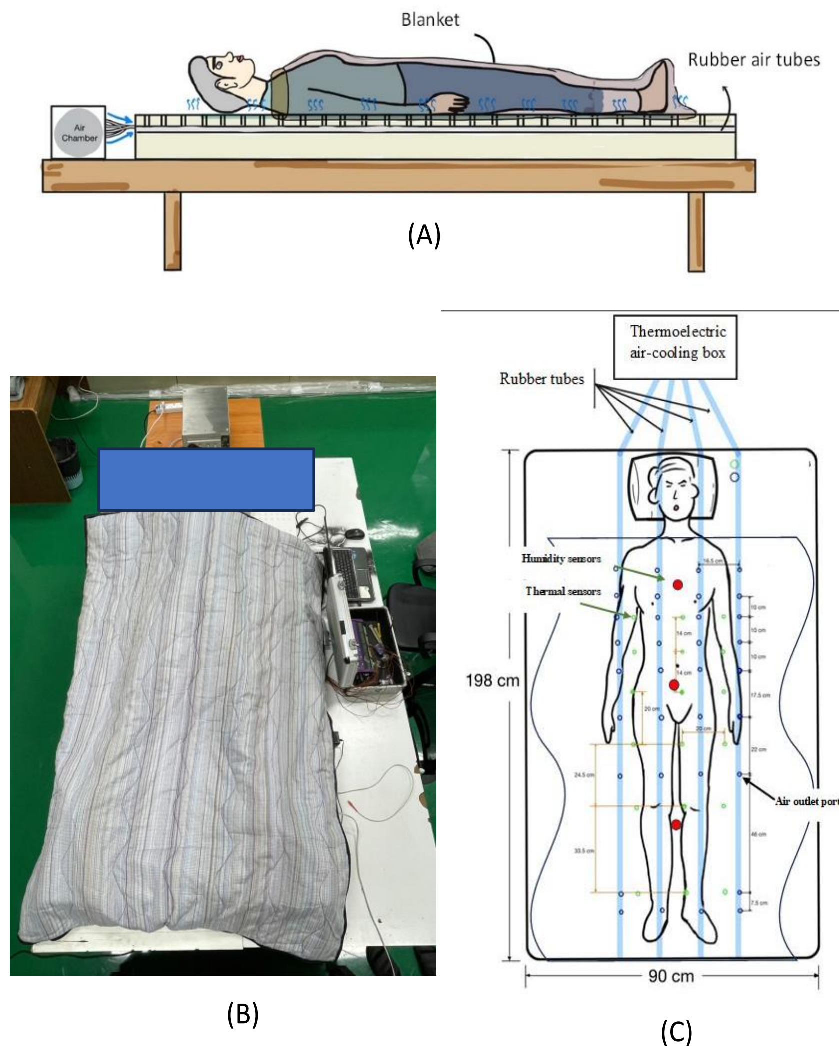

Fig. 1 The measured temperature positioning.

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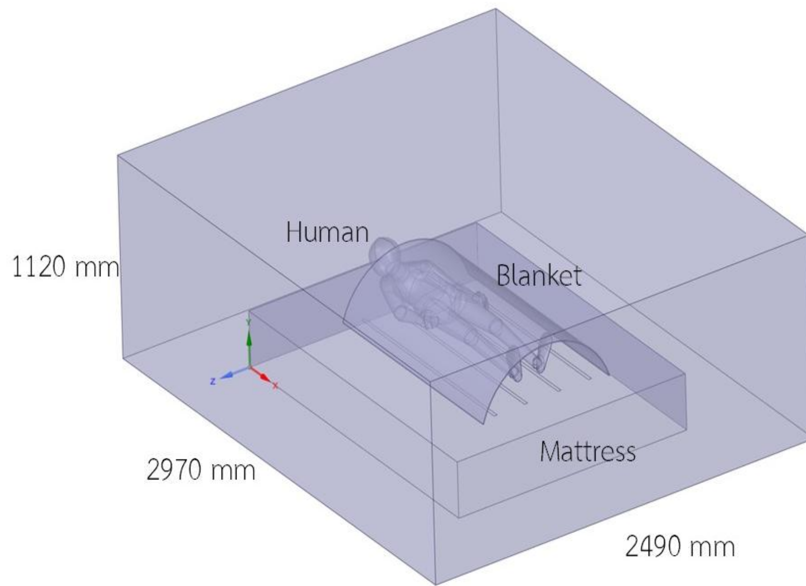

Fig. 2 Diagram of the computational domain used in the present study.

3. Mathematical modeling

In a computational technique, a mattress with a cooling system is numerically assessed, as shown in Fig. 2, with dimensions and necessary computing domains. The heat transfer mechanism between the mattress, human skin, and the blanket is assumed to be distributed across the subject body under the following assumptions:

- There is a turbulent single-phase steady-state 3D flow condition.
- Adiabatic boundary conditions exist on the exterior surface.
- Changing the thermophysical characteristics of the air under the cover is not authorized.
- Constant airflow qualities of the mattress are evaluated.
- Radiative and convective heat transmission are not addressed.
- The blanket covering the human is assumed to be the inverted bell shape.
- The heat generated by the subject body is constant.
- The blanket is assumed to be the insulation layer with 2 mm thickness.

Table 2. Boundary conditions were used in the analysis.

Parameters	Values
Generated heat from the subject, ($\mu W/m^2$)	30
Room temperature, ºC	25, 30
Inlet cooling air temperature, ºC	22
Cooling air velocity, m/s	2.65

Using the basic governing equations,[63,64] the flow model is utilized to analyze the following problems:

$$\frac{\partial \rho}{\partial t} + div(\rho U) = 0 \quad (1)$$

$$\rho \frac{DU}{Dt} = -\frac{\partial p}{\partial x} + div(\mu gradU) + S_M \quad (2)$$

$$\rho \frac{DT}{Dt} = -pdivU + div(\Gamma gradT) + \Phi + S_i \quad (3)$$

Turbulent model:

$$\frac{\partial(\rho k)}{\partial t} + div(\rho kU) = div\left[\left(\frac{\mu_t}{\sigma_k} gradk\right)\right] + 2\mu_t E_{ij} \cdot E_{ij} - \rho\varepsilon \quad (4)$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + div(\rho\varepsilon U) = div\left(\frac{\mu_t}{\sigma_\varepsilon} grad\varepsilon\right) + C_{1\varepsilon}\frac{\varepsilon}{k} 2\mu_t E_{ij} \cdot E_{ij} - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \quad (5)$$

Boundary and initial conditions:

$$q_{wall} = 0\ ,\ u = u_{in}, v = 0, w = 0, \varepsilon = \varepsilon_{in}, k = k_{in}, T = T_{in} \quad (6)$$

$$\varepsilon_{in} = C_\mu^{3/4}\frac{k^{3/2}}{L_e}, k_{in} = \frac{3}{2}(u_{in}I)^2, I = \frac{u'}{u} \times 100\% \quad (7)$$

Launder and Spalding presented the constants as, $C_\mu = 0.09$, $C_{\varepsilon 1} = 1.47$, $C_{\varepsilon 2} = 1.92$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$.[63]

The problem is investigated using a turbulent flow model and numerically solved using ANSYS as the solver.[65] The boundary conditions used in the numerical analysis are listed in Table 2 with the grid configurations as shown in Fig. 3. To gain calculation accuracy, the grid-independent test is done on several grids, as seen in Fig. 4. The final calculation uses a residual total of 10^{-6}. The variation of body human temperature with the number of grids is shown in Fig. 4(A). In addition, it can be seen from Fig. 4(B) that the surface human temperature of 1.2×10^6 is less than 1% finer than that of 10^6; using the 10^6 grid assures reliable results.

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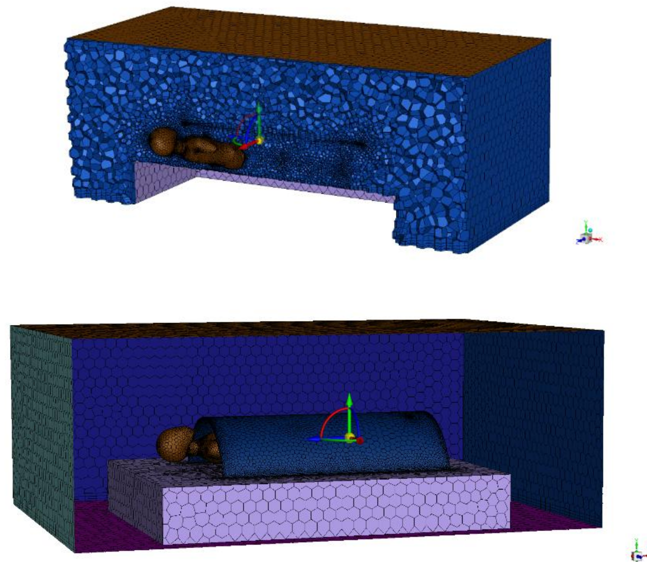

Fig. 3 Grid characteristics used in the present numerical study in XY plane.

4. Artificial neural network approach

ANNs are among the most promising computer intelligence methods. However, developing an ANN is tough since it requires establishing an ANN structure and modifying complex parameters. Nonlinear mathematical models of ANNs are becoming more popular due to their simplicity, flexibility, many training techniques, and tremendous modeling potential. In general, the neuron obtains input parameters before producing an output parameter that may be sent to many neurons (Details can be seen in the text by Haykin).[66] Bayesian regularization neural networks are considered more reliable, long-lasting, and efficient than typical backpropagation networks, and they may decrease or eliminate the requirement for cross-validation throughout the learning process. To offer a more detailed explanation of Bayesian regularization, the method employs ridge regression, a mathematical technique that converts a nonlinear regression issue into an equally well-posed statistical assignment. The Levenberg-Marquardt technique often uses backpropagation to calculate the performance's Jacobian 'jX' while accounting for bias factors X and weight. Using the fundamental concepts of the Levenberg-Marquardt algorithm, each variable is modified in the following ways:[66]

$$jj = jX * jX \tag{8}$$

$$je = jX * E \tag{9}$$

$$dX = \frac{-(jj+I*mu)}{je} \tag{10}$$

where E is all errors, I is the identity matrix, and mu is the adaptive controlling parameter.

The tangent function activates the hidden layer, whereas the linear function activates the output layer. Backpropagation is an approach to network training. Backpropagation calculates the degree of inaccuracy as the difference between the processed sample from the input to the output layer and the intended value. During the training phase of an ANN model, predicted outputs are compared to input data. The number of

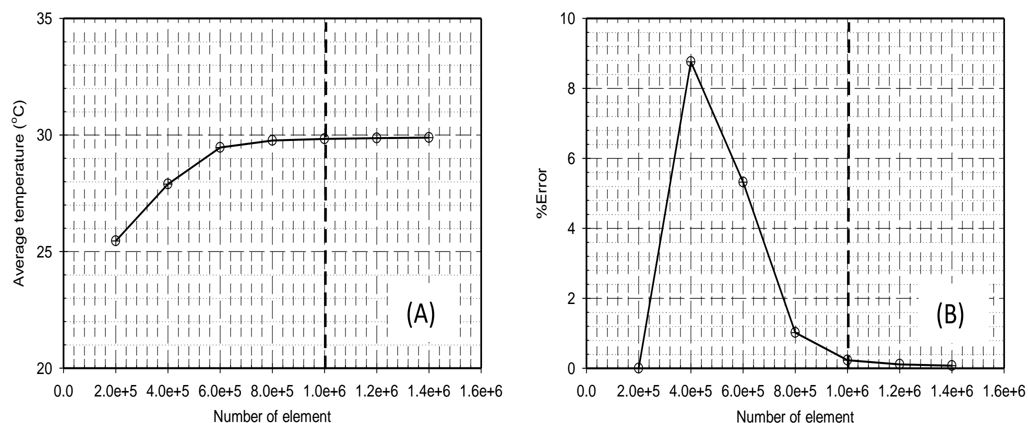

Fig. 4 Grids independent test for (A) average temperature, (B) %Error.

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nodes may be calculated using physical attributes. Neural network training and testing need input data patterns and targets. When developing an ANN model, the datasets are divided into train the model (60%), verify the model (20%), and another dataset (20%) is used in the testing process. Weights and biases are adjusted to reduce the expected output and input data disparity.

A regression process may be performed to evaluate the upgraded ANN model's performance based on the expected results. The correlation coefficient (R) and mean square error (MSE) are employed to evaluate the accuracy and ensure that the ANN model's training and forecasting processes are consistent. The R can be calculated as follows:[67]

$$R = \frac{cov(a,p)}{\sqrt{cov(a,a) \cdot cov(p,p)}} \quad (11)$$

where *cov(a, p)* is the covariance between the sets *a* and *p*, which represent the observed data and projected outcomes derived by ANN, respectively, and is determined using:

$$cov(a,p) = E\left[(a-\mu_a)(p-\mu_p)\right] \quad (12)$$

E represents the expected value, whereas μa and μp represent the mean values of *a* set and *p* sets, respectively. Furthermore, *cov(a, a)* and *cov(p, p)* represent the auto covariances of *a* and *p* sets, respectively, and are stated as follows:

$$cov(a,a) = E[(a-\mu_a)^2] \quad (13)$$

$$cov(p,p) = E\left[\left(p-\mu_p\right)^2\right] \quad (14)$$

The mean square error (MSE) is determined based on [67]:

$$MSE = \frac{1}{N}\sum_{i=1}^{N}(a_i - p_i)^2 \quad (15)$$

where a_i and p_i are the experimental data and anticipated outcomes for *i* set, and *N* is the number of data patterns.

5. Results and discussion

5.1 ANN structure optimization

A conventional sensitivity analysis is employed to choose an acceptable model. When creating an ANN, the datasets are separated into three datasets: train the model (60%), validate the model (20%), and the third (20%) utilized in the testing phase.[68] Training terminates after the goal MSE is reached or after a certain number of completed epochs. Fig. 5 depicts the three layers of the network employed in this article. In the ANN setup model shown in Fig. 5, the input parameters are sex, body mass index (BMI), room temperature, and cooling air temperature, with the mattress temperature as the output parameter. The output layer has a single node: the body surface temperature. The node number in hidden is computed using the prior procedures and ranges from 1 to 9. With more neurons, the networks may produce numerous R and MSE values throughout the training phase.[69,70] We examined the

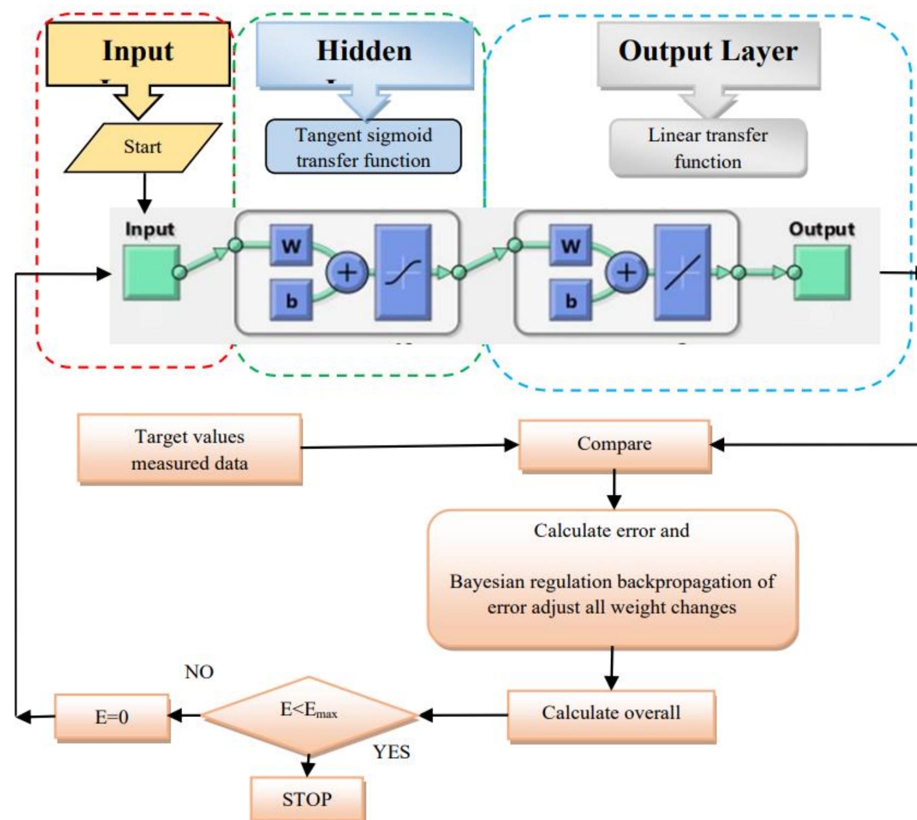

Fig. 5 Proposed optimal ANN model configuration.

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transfer functions in the network's hidden and output layers. We also do a typical sensitivity analysis to determine the ideal number of hidden neurons. The MSE was shown to decrease constantly as the number of hidden layers increased from 1 to 9. As the hidden layer three is added, the MSE difference between the three datasets becomes the smallest. When the number of hidden layers reaches three, the MSE rises somewhat.

The experimentally collected body surface temperature data is utilized in ANN analysis. Fig. 6 indicates that the program has a reduced mean square error at epoch 1000, with a gradient of 0.054496. The optimal training performance is 34.4759 at epoch 1000. The proximity of sample data to the equality line indicates good performance. The correlation coefficients R^2 for the training, testing, and all datasets are 0.9911, 0.9986, and 0.9916, respectively, as shown in Fig. 7. The R^2 values for all datasets are close to one, indicating that the generated model is well-trained and provides the highest performance for predicting body surface temperature data. Prediction errors for training, testing, and all datasets are within the ±2.5% error range.

5.2 Verification of the predicted numerical results

It is revealed that no previously published data under comparable conditions exist to substantiate the cited conclusions. Three sensors were used to measure humidity while the subject slept on the mattress, and eighteen thermocouples were used to monitor temperature changes between the mattress (subject) and the cover, as shown in Fig. 1. The measured data may be confirmed by comparing the numerical findings. Fig. 2 depicts the three-dimensional computational domain constructed using SolidWorks software.

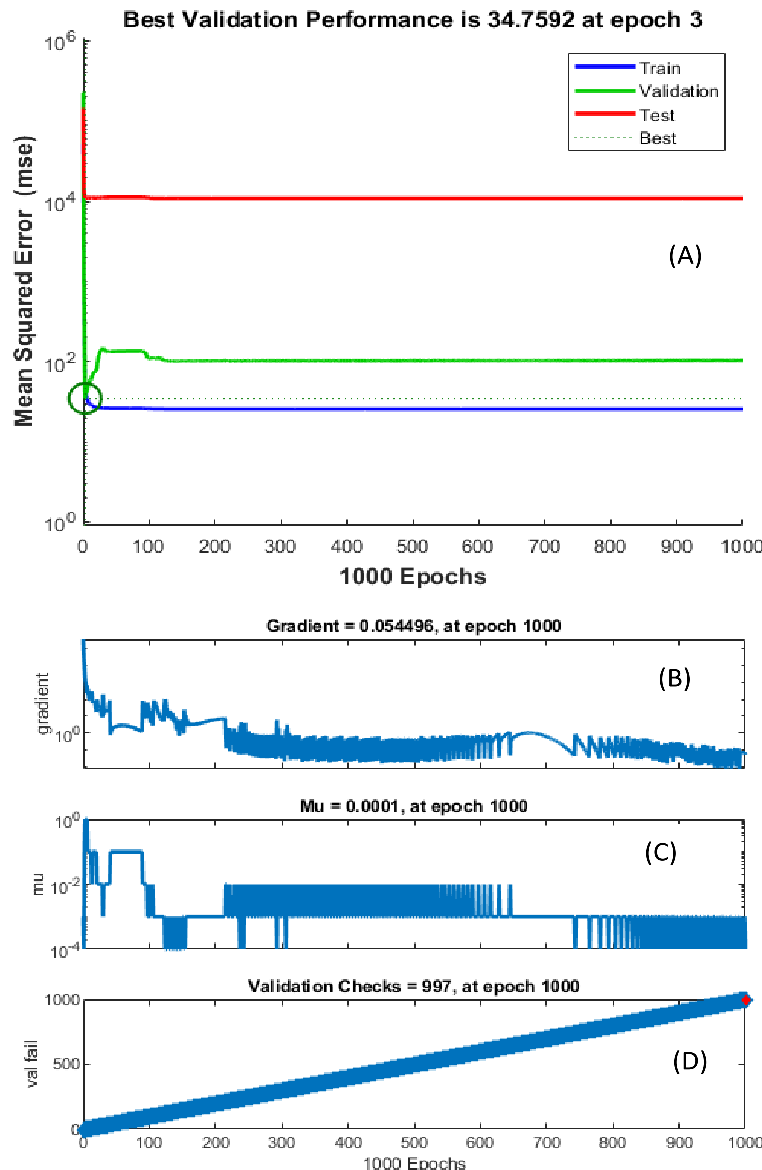

Fig. 6 Variation of MSE with epochs for optimal ANN model in the training process.

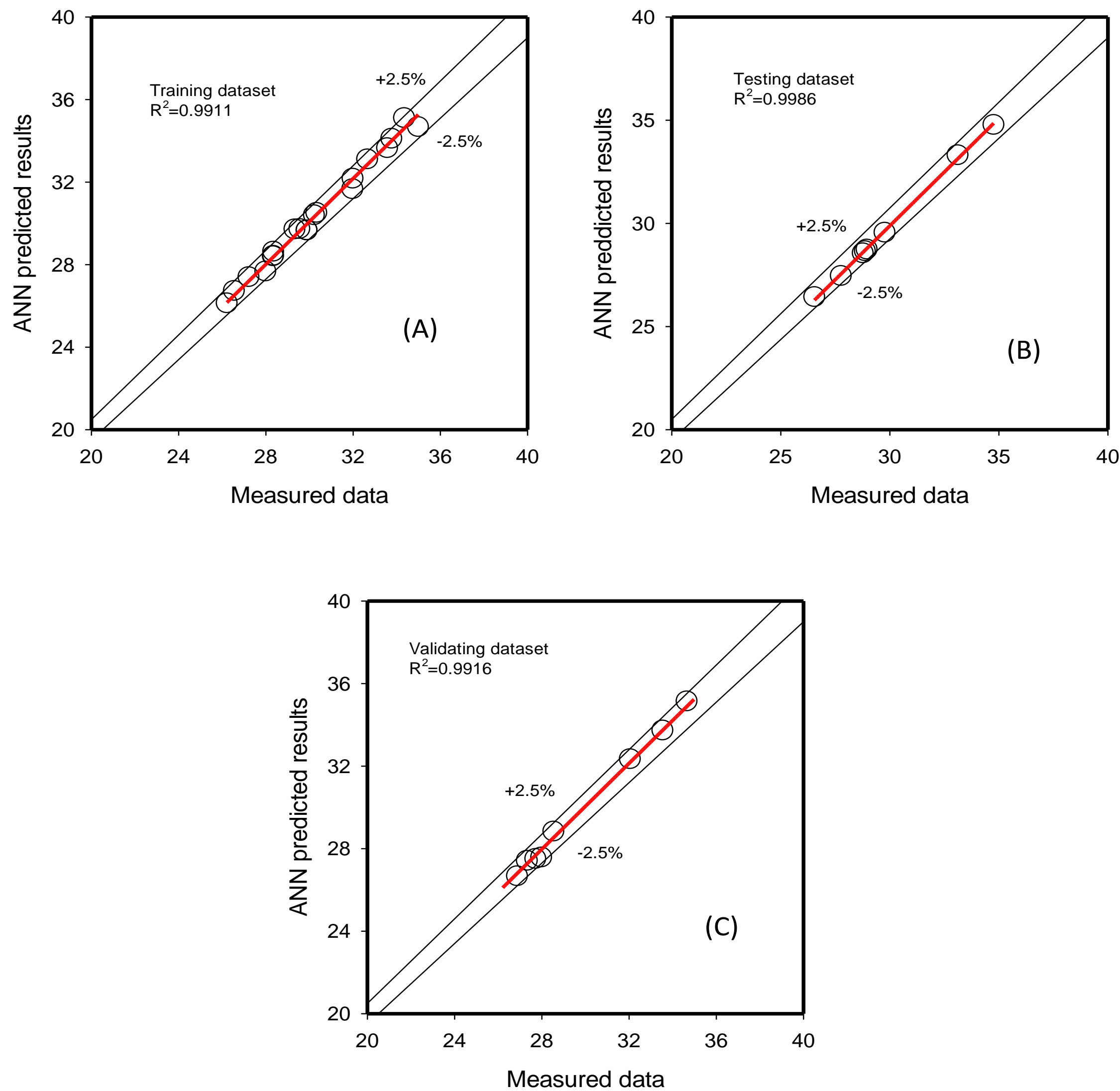

Fig. 7 Comparison between the measured temperature and ANN predicted results, (A) Training dataset; (B) Testing dataset; (C) Validating dataset.

Commercial software Ansys Fluent was used to handle the pressure-velocity coupling issue throughout the simulation phase. Table 3 compares the observed data to the projected numerical values, which are relatively consistent with errors of 7.53% and 5.96% for input cooling air temperatures of 25 °C and 30 °C, respectively. In addition, Table 4 compares the observed body surface temperature to the numerical results and previous findings.[71–73] The body's surface temperature error is 5.08%,[71] 9.32%,[72] and 6.46%.[73] Furthermore, the thermal imaging camera is utilized to assess human temperature distributions, which are then compared to the predicted results, as shown in Fig. 8. It can be seen that the top and lower zones see the highest and lowest average temperatures, respectively.

Due to the collected heat from the human body, the mattress temperature tends to rise, reaching a maximum of 34-36 ºC with increasing operation duration. The body's metabolism, which accelerates during work, generates heat continuously. During this period, airflow across the skin promotes metabolic cooling. The human body has several thermoregulation mechanisms in the limbs, feet, hands, head, and chest. Surface area, tissue conductivity, local heat generation, and other factors all influence heat transfer. It is suggested that distinct body parts have different cooling needs. Body surface temperature increases proportionately to tissue metabolic demand, with a 10% increase for every 1°C increase in skin temperature.[74,75] The risk of PU increases as the sacral skin temperature is above 35 °C.[14] Furthermore, every 1 °C raises the damage score by 13.0 to 15.0 times that of a single mmHg.[12] Patients with PUs may benefit from a variety of treatment and prevention techniques. There have been reports of various support surfaces like cushions, alternating pressure beds, compressed air beds, and mattress temperatures.

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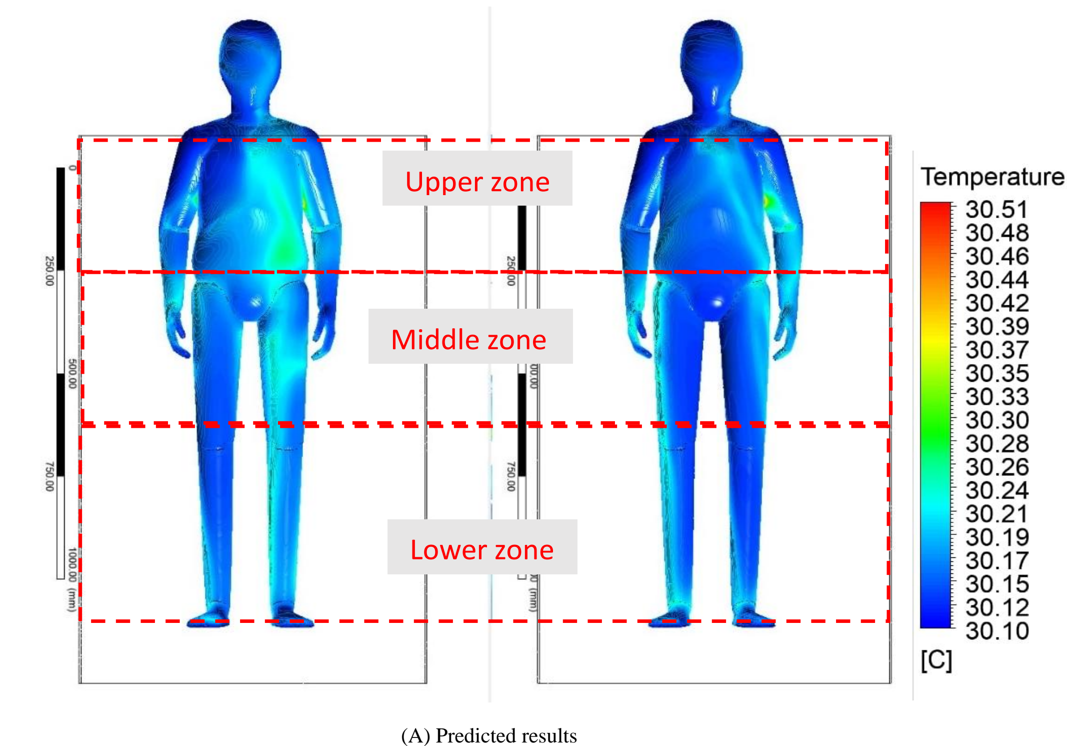
Table 3. The comparison of body surface temperatures obtained from the predicted results and the measured data.

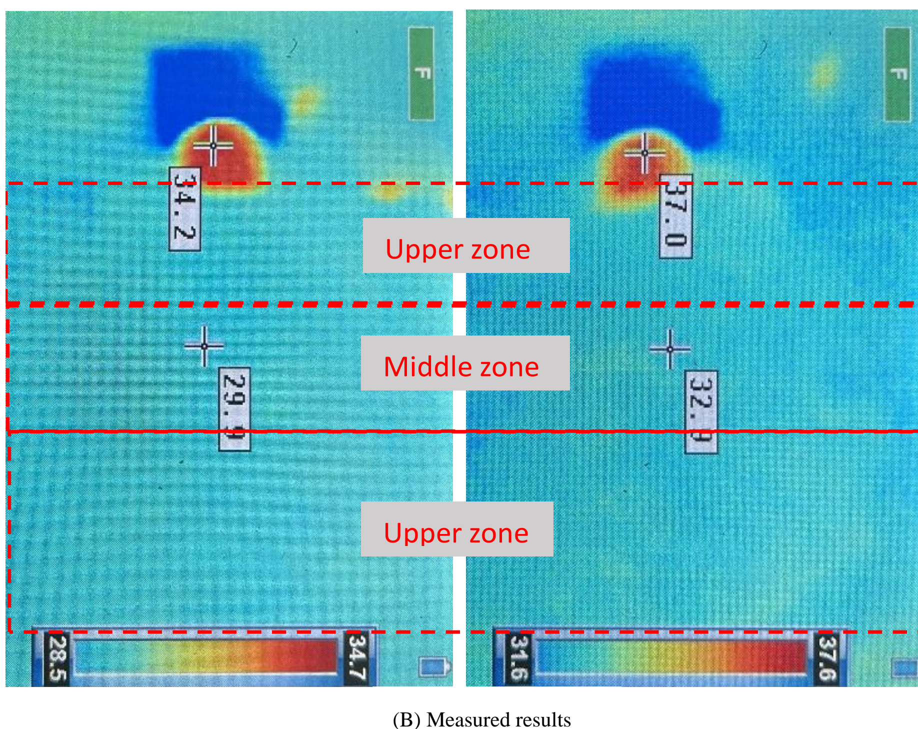
Room temperature (ºC)	Average temperature at upper zone (ºC)		% Errors
	Measured data	Predicted results	
25	27.41	25.42	7.53
30	31.94	30.09	5.96

Table 4. The comparison of surface temperatures was obtained from the predicted results and the published data.[71-73]

Body positions	Average body temperature (ºC)			
	Yang *et al.*	Zaproudina *et al.*	Webb *et al.*	Present predicted/measured results.
Back	30.6	32.5	34.4	30.09/32.43

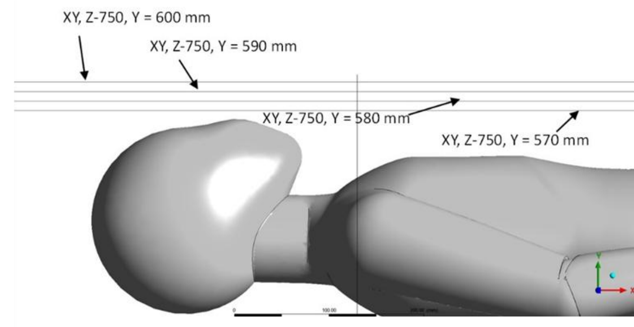


(A) Predicted results

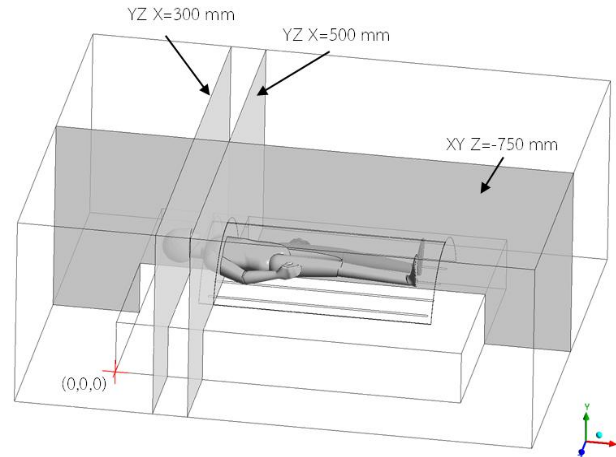


(B) Measured results

Fig. 8 Comparison between the predicted results and the measured data (Surface temperature).



(A) Difference Y layers in XY plane



(B) Difference X layers in YZ plane and Z layer in XY

Fig. 9 Reference positions of the model used in the present the predicted results.

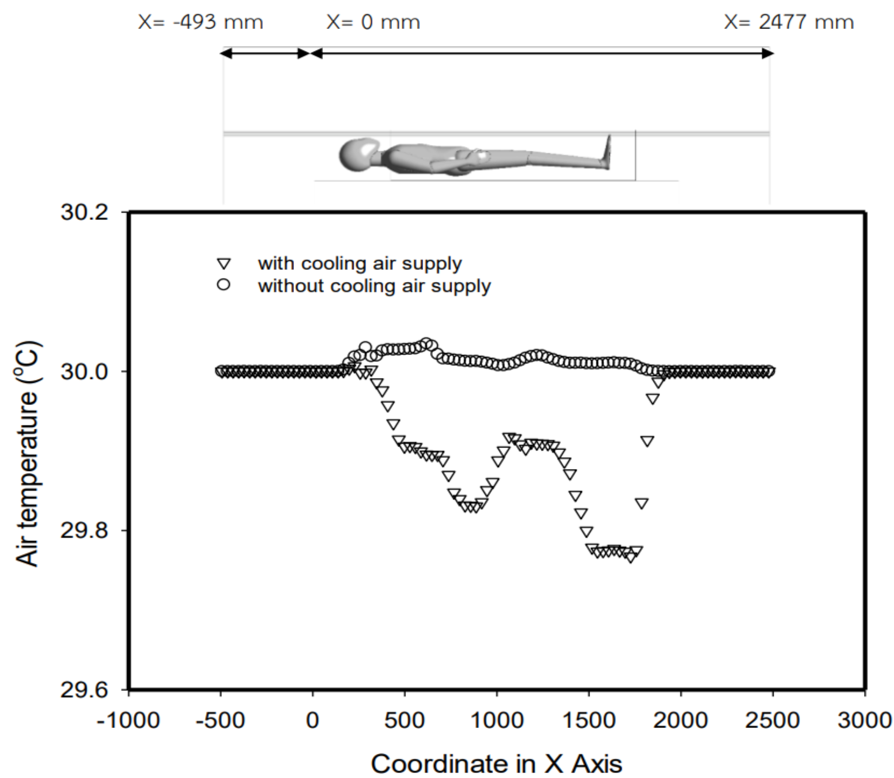


Fig. 10 Air temperature distribution inside the blanket of XY plane at Z=-750 mm, Y = 570 mm for a room temperature of 30 °C with and without air cooling system.

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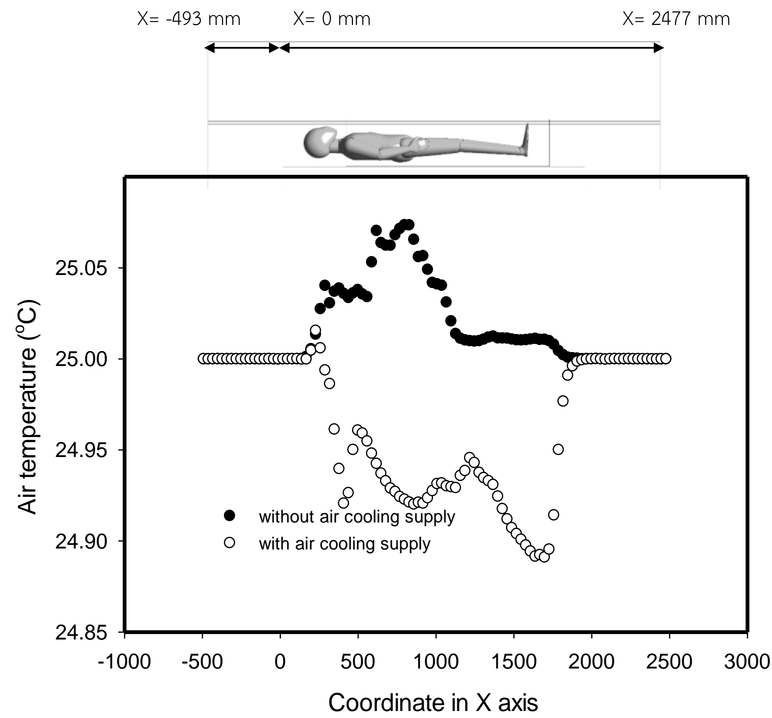

Fig. 11 Air temperature distribution along the X axis inside the blanket of XY plane at Z=-750 mm, Y = 570 mm for a room temperature of 25 ºC with and without an air cooling system.

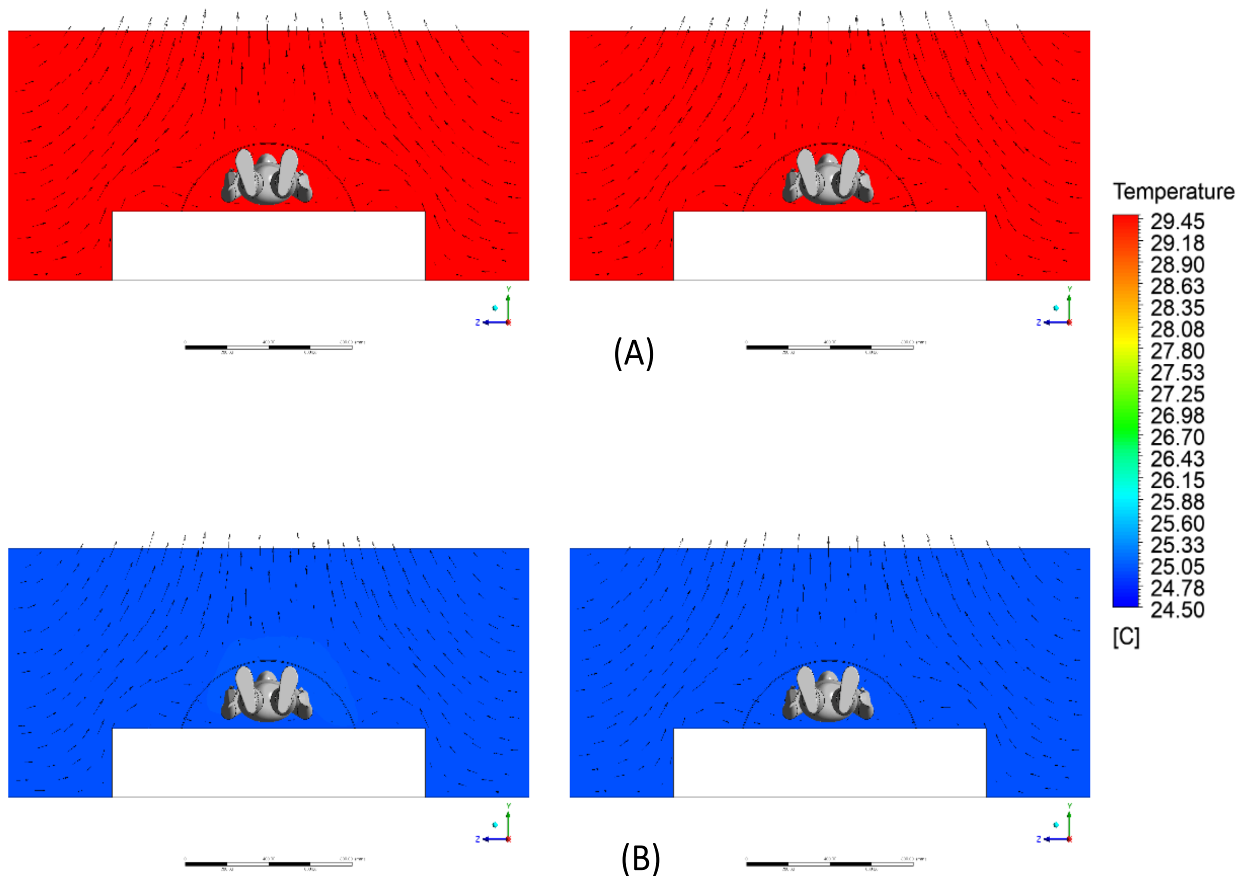

Fig. 12 Velocity vector in YZ plane, X=300 mm at room temperature of 25 ºC (A) with and (B) without air cooling system.

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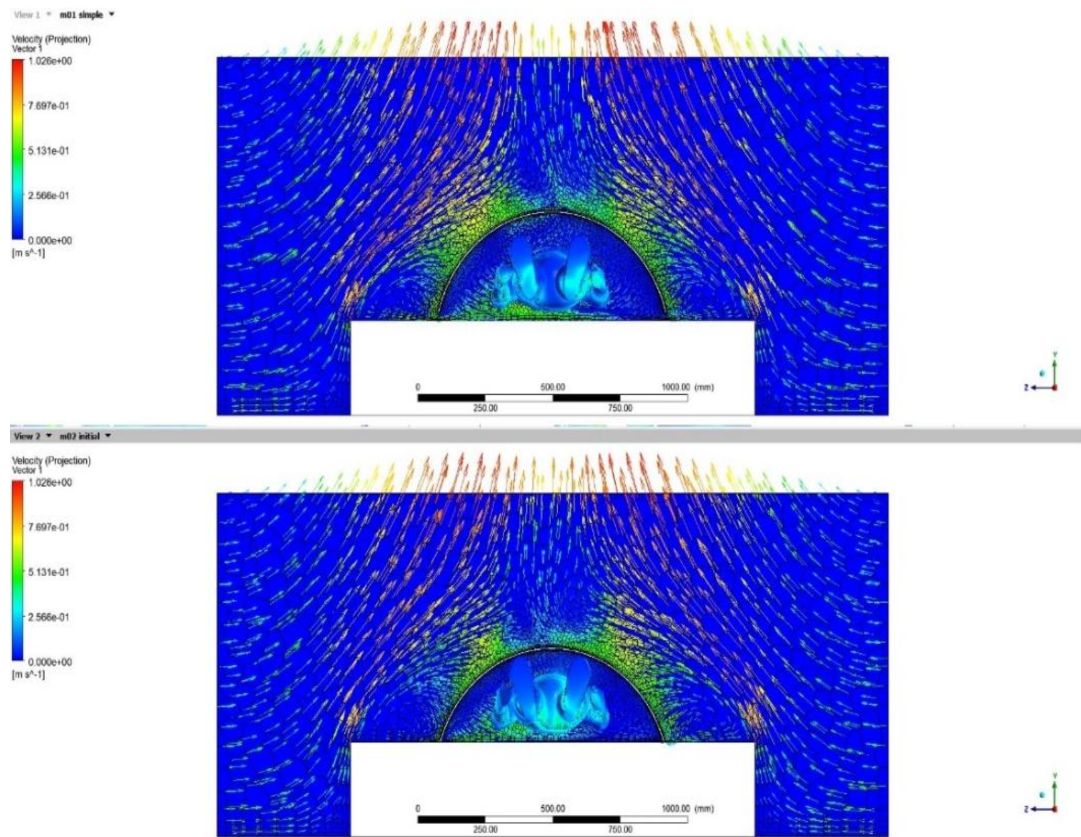

Fig. 13 Velocity vector of air outside the blanket.

Figure 9 illustrates selected model cross-sections used to demonstrate the finding results. As mentioned above (Fig. 8), the top zone has the highest body surface temperature. Thus, the projected results from the numerical analysis are given there. Figs.10 and 11 depict the fluctuation in air temperature distribution in the XY plane at Z=-750 mm, Y = 570 mm for room temperatures of 30 ºC and 25 ºC, with and without an air-cooling system. In the numerical analysis procedure, the subject-generated heat from the body surface is held constant at 30 μW/cm^2 (20-50 μW/cm^2 at 28 °C),[76,77] the input cooling air temperature at 22 °C, and the cooling air velocity at 2.65 m/s for an air-cooling system. In the current study, the individual is lying on his back, covered with a blanket. The body generates the greatest heat in its upper and middle zones. The human body releases heat in four ways: evaporation, convection, radiation, and conduction, which transmit heat from the subject's body to the air within the blanket. Without a cooling air system, the air temperature and moisture within a blanket are greater than outside, particularly in the subject's upper and middle zones, causing thermal discomfort. As a result, the ventilated mattress determines if airflow through the mattress is necessary for local body cooling. Air cooling has been shown to reduce the local warm thermal feeling (lower temperature and moisture), particularly on the behind and back. This impact of the mattress will benefit bedridden patients exposed to high air temperatures. However, substantial changes in local thermal feeling due to non-uniform body cooling may produce thermal discomfort. Individually controlled heating of the mattress surfaces in touch with the body is possible within a reasonable range of room air temperature.

Figures 12 and 13 illustrate the simulated airflow and temperature distribution within and outside the blanket. The air around the subject's body was warm. Overall, the subject's body temperature was greater. In contrast, the bottom zone consistently had the lowest temperature. The airflow entered the subject via the opening port beneath the mattress, and the flow velocity decreased quickly. Some airflow flowed across the body, while others circulated within the blanket, exiting through the aperture in a lateral orientation. The buoyancy effect causes air to travel up along the lateral surface of the blanket into the environment, as seen in Fig. 13.

5.3. Limitations of the study

In the experimental process, it is difficult to perform tests on bedridden or elderly patients without disrupting the rest of the patients. Thus, the first study was carried out on healthy Thai students. Furthermore, individuals were discovered lying in bed on their backs. Volunteers may prefer to sleep face down or on one side in reality; however, it is unclear how this may

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affect their thermal comfort while utilizing a cooling system. The study's participants are healthy people. Participants in the trials comprised young men and women of various heights, weights, and BMIs. Participants of various ages and physiological parameters were not permitted to participate in the research. Furthermore, the mattress's temperature is heavily influenced by the surrounding environment. The numerical analysis demonstrates the limits of this procedure via the assumptions described above and the usage of additional datasets in the ANN process.

6. Conclusion

An ANN approach measures the mattress temperature (body surface) of elderly and bedridden patients. We also validate the current ANN model by comparing it to numerical findings, observed data, and published results. It was discovered that the ANN model provided greater agreement. The ANN technique, numerical model, and published findings were compared with experimental data at 25 °C and 30 °C room temperatures. Furthermore, the ANN model has a maximum error of 2.5%, while the numerical model yields 7.53% and the published findings 9.32%.[73] The findings indicate that the ANN technique is a potential tool for monitoring body surface temperature, successfully reducing the incidence of pressure sores in elderly and bedridden patients.

Nomenclature

C_p specific heat, kJ/kg °C
I turbulent intensity
k turbulent kinetic energy, m^2/s^2
p pressure, kPa
L turbulent characteristics length, m
T temperature, °C
t time, s
U velocities vector
u,v,w velocities, m/s

Greek symbol

ε dissipation kinetic energy, m^2/s^3
μ_τ dynamic turbulent viscosity
ρ density, kg/m^3
μ viscosity, kg/ms
Φ viscosity energy dissipation function

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Conflict of Interest

There is no conflict of interest.

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Supporting Information

Not applicable.

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