International Journal of Engineering Science Invention (IJESI)
ISSN (Online): 2319-6734, ISSN (Print): 2319-6726
www.ijesi.org ||Volume 10 Issue 3 Series I || March 2021 || PP 39-46

Design and Development of Novel Warm Mattress for Medical Application

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Abstract.*Magnetic Resonance Imaging (MRI) and other similar medical imaging are conducted in temperatures well below the nominal room temperature ,which is between 21 to 24℃. This cold environment triggers shivering and also a biochemical response which results in the formation of brown fat. Both these thermogenesis processes hinder the imaging process there by reducing the accuracy of the scanned images. The extended period in a cold environment and limited physical motion causes discomfort and fatigue. The existing means of providing warmth is not compatible with MRI and Computed Tomography (CT) scans safety requirements, which restricts the presence of a metallic heating element. In this paper, a novel concept and design for Warm Mattress have been developed which is compatible to safety norms. Convective mode of heat transfer is employed to provide warmth to the patients. This method is adopted to keep the heating element far away from the MRI machine.*

Keywords:*Warm Mattress, MRI compatibility, Medical Imaging, convective heat transfer.*

Date of Submission: 03-03-2021 Date of Acceptance: 16-03-2021
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I. INTRODUCTION

The core temperature of the human body lies between 36-37°C. When this temperature drops below 35°C, shivering reflex is triggered to maintain homeostasis, i.e. to maintain steady core temperature. The shivering is caused by small shaking- movement by skeletal muscle, for creating warmth by expending energy. This often leads to fatigue after being exposed to a cold environment for a while. The body also adopts non-shivering thermogenesis. When exposed to cold temperatures, the adipose tissue is metabolized to glycerol and non-fatty acids. And these molecules are further degraded to generate heat. This biochemical phenomenon is called the formation of brown fat(1). And this is for more pronounced when the body movements and muscular motions are limited. A similar situation prevails in the medical imaging rooms of the hospitals and scanning centers, where the patient's body motion is limited and are exposed to cold temperature since the imaging rooms has to be maintained at a low temperature for proper functioning and to prevent failure of the machine, or on worst case-catastrophic damage. Typically the temperature of the Computed tomography (CT) scanning room is kept between 17 to 21° C and the MRI imaging room is maintained at 21° C +3°C(2). Thus, when a patient is undergoing imaging process, they are subjected to an extended period of exposure to a cold environment which causes intensive shivering and involuntary shaking of the body especially in young, old, and medically ill people and also causes the formation of brown fat, which more pronounced in infants. These biological responses to maintain the body temperature hinders the imaging process to a certain extent. The small muscular movements during the shivering cause distortion in the scanned image and the formation of brown fat make it difficult to get a clear image of the internal organs.

To reduce the effects of the low temperature, patients are provided with a blanket. But this is proven to be not of much use against the cold condition of the room. And also, the blankets are sterilized for each patient. this also requires a lot of maintenance. Thus, active heating aids such as heating blankets or warn mattresses are needed to provide warmth to patients in the imaging room. Heating blankets use nichrome wires as a heating element, which is embedded in the fabric of the blanket, and when the current is passed, the wire generates heats due to the resistance heating and makes the blanket warm. But the presence of metals in the MRI scanning room is restricted. Interaction of the metal the MRI machine may cause catastrophic outcomes due to the huge magnetic field(~4 Tesla) produced in MRI machines(3).The warm water mattress by Kanmed Sweden is used for keeping newborn infants warm. A metal heater generates heat and this heat is conducted through the water in contact with the bed to provide warmth to the babies. Since the water is diamagnetic, its interaction with the magnetic field of MRI tends to distort the image produced by Magnetic Resonance. Using liquid-based heating set up requires extensive maintenance and spillage has the potential to damage the scanning machine. There is currently no method for delivering warmth and comfort to the patients in the imaging room.

In this paper, a new concept for the warm mattress is introduced which tries to eliminate all the complications discussed above and to be MRI and CT compatible. The possibility of any interaction between the magnetic field of the MRI machine and metal components is avoided by keeping the metal heating element is the far vicinity. The heat generated by the nichrome wire heating element is carried to the mattress using the convective mode of heat transfer- using air as the medium. The design of the mattress will also involve a means to evenly distribute the air throughout the mattress and a real-time temperature monitor and control settings with the optimum response time.

II. METHODS EMPLOYED

Convective mode of heat transfer is employed to heat the mattress surface which comes in contact with the patient's body. The heat is convected through the gaseous medium rather than a liquid medium to avoid spillage of the fluid, avoiding the use of a dedicated pump and reducing the overall complexity of the design. The gas involved in heat transfer is atmospheric air. The heat required for the mattress is generated by a resistance heating element and it is transferred through convective currents induced by an external source such as a fan or a blower. The hot stream is blown below the surface of the top layer of the mattress. The hot air is uniformly distributed beneath the top layer with the assistance of a dedicated distributor assembly. The distributor is supplied with the hot stream of air through one or more inlets and comes out through multiple outlets present on the top surface of the distributor. To ensure the proper distribution of the hot air, the interior of the distributor comprises a honeycomb structure. This structure promotes localized low-velocity turbulent flow(4) in the convective current within the distributor. The turbulence ensures the efficient distribution of heat.

Another functionality of the honeycomb structure is to prevent the deflating of the distributor due to the patient's body weight. Since the top layer is impenetrable to air, the air is re-circulated back into the blower. This forms the closed-loop circulation of the working fluid (air in this case). This prevents the build-up of back pressure inside the mattress. The recirculation of the air also minimizes the energy consumption of the heating element. The material used in the Distributor is intended to have low thermal conductivity to prevent the loss of heat from the hot air to the distributor. And the material used for the top layer is to have the thermal conductivity value within the optimum range of to obtain the intended amount of heating using the equipped temperature regulator with the response time as low as 3 seconds and with the minimal requirement of energy. The temperature of the air at the inlet is regulated by a temperature control module as per the patient's requirement. Since the presence of any metal component in the vicinity of the magnet field produced by the MRI machine, the thermostat cannot be equipped on the Mattress and hence it is placed at the inlet of the distributor and the temperature control module can be calibrated accordingly. The heating coil temperature is dynamically controlled and adjusted to deliver the required amount of heat.

III. MATERIALS

Table 1.Materials used and their thermal conductivity(5)

S.No.	Materials Used	Materials used Thermal Conductivity @30℃(W/mK)
1.	Polyurethane (Grade 50)	0.022
2.	Polyvinylchloride	0.17
3.	Rexine	0.25-0.28

3.1 Polyurethane – PU

The Base-PU foam is used for the Base of the Warm mattress. The foam of grade 50 is used for rigidity and robust structure. the low thermal conductivity (0.022W/mK @ 30°c) of the Polyurethane prevents the loss of heat from the hot air into the surrounding through the mattress. This ensures the heat is utilized for warming only the required space.

The Distributor - PU sheets are made into an envelope to form the distributor. Again, polyurethane is used to prevent the loss of heat.

3.2 Polyvinylchloride (PVC) [Plasticized]

Plasticized PVC is used for the construction of the Supporting Frame for the distributor. The plasticized PVC is flexible and can to a certain extent without any structural failure load is applied.

3.3 Rexine

The Rexine is used for the topmost layer of the Mattress which comes in contact with the patient's body, ergo this is the surface that's needed to be heated. Thus, the thermal conductivity (0.27-0.28 W/mK @ 30°c) of the Rexine is relatively higher than that of all other materials used, to make sure that the most for the heat from the hot air is transferred to it. The Rexine is also called artificial leather. The major component of Rexine is cellulose nitrate, which is surfaced on to Fabric, and embossed to look like leather.

IV. Design

The dimensions of the design are as per the problem statement proposed by the General Electric's Healthcare(6). The mattress dimensions are; 2 meters length × 0.42 meters width.

4.1 Base

Polyurethane foam block of Grade 50(Nominal density of 50 kg/m^3) forms the base for the mattress Fig. 1. The PU form is widely used material for mattresses and cushions in the medical field due to its durability availability and low cost.

The base incorporates the heating module or – the distributor, which heats the surface of the Mattress.

Fig. 1.The base

4.2 Distributor

The distributor intakes in the hot air and uniformly distributes it and is placed right beneath the topmost layer. Fig. 2

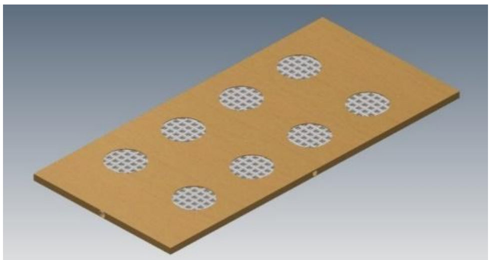

Fig. 2.Distributor

The distributor set up comprises of two components

Distributor – Polyurethane sheets (PU) envelope. The Distributor is a PU sheet (3mm) envelope which takes in hot air through one or more inlets (depending on the surface area to be heated) and distributes it uniformly through appropriately positioned outlets.

This air comes in contact with the bottom surface of the top layer and the heat is transferred across the layer which comes in contact with the patient's body. Fig. 3

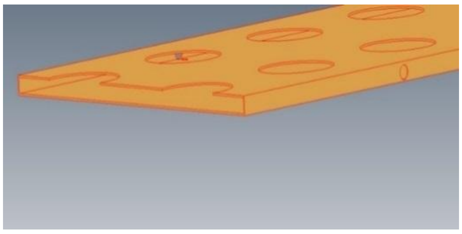

Fig. 3.Distributor – PU sheets

Distributor – Supporting Frame. Distributor supporting frame (PVC wire mesh) with 2.5inch×2.5inch weave, stacked up in multiple layers to achieve the required thickness, and is as indicated in Fig. 4.The supporting frame has two main functionalities (1) The frame prevents the distributor envelope from deflating due to the bodyweight of the patient & (2) the multiple layers of wire mesh forms a honeycomb structure which promotes a low-velocity localized turbulent flow (geometry induced). This accelerates heat transfer as turbulent flow cause proper thermal mixing.

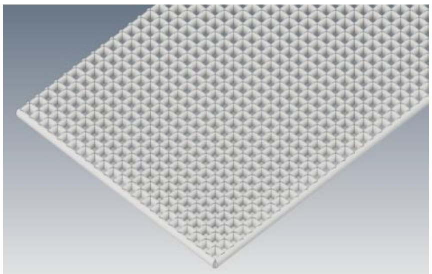

Fig. 4. Distributor – Supporting frame

4.3 Inlet and Outlet

The inlet and the outlet port of the closed-loop circulation are constructed using PVC pipes. This is chosen for its durability, availability and low cost. The connections are secured using rubber seals to make it leak proof.

4.4 Heat element

The heating element delivers hot air, which the prime medium of heat transfer employed in the model. The heating element comprises,

- Heating coil
- Blower fan
- Temperature control module

The Heating coil is used to generate the heat required, which will subsequently be carried by air through convective heat transfer. The coil used in the model is rated at 2000 W (Max). The air current is generated with the help of an axial fan powered by a single-phase AC motor rated (220 V) and reaches the speeds from (10,000 to 15,000 RPM). A variable temperature control module is used to achieve the preferable mattress temperature in accordance with the requirement of the patient. The temperature control module is equipped with,

- Thermometer
- Temperature controller IC W1209 Fig. 5

Fig. 5Temperature Controller

The thermometer measures the temperature and if it is not the same as the temperature intended by the user (Temperature selection can be performed using temperature selector), IC acts as a switch that constantly switches on/off the heating element until intended temperature is achieved and maintained constant. The circuit diagram is represented in Fig. 6

Since the presence of any metal component in the MRI machine, the thermostat cannot be equipped on the Mattress itself. Thus, it is mounted in the inlet of the hot air pipe.

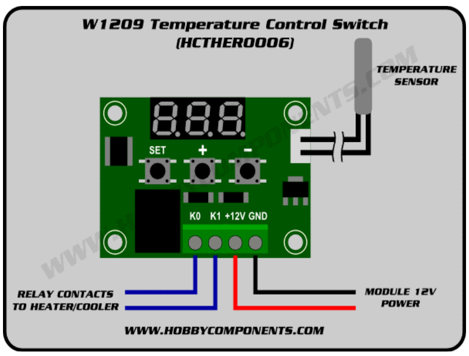

Fig. 6.Basic circuit layout

4.5 Top layer/ Outer cover

The outer cover used for the mattress is Rexine/ artificial leather of 3mm in thickness. This is the most common material used in cushions, pillows, and mattresses in the medical field because its non-reactive, waterproof, easy-to-clean properties and are economical.

Nylon as an alternate to the Rexine was considered a possible candidate due to similar thermal conductivity and availability. But X-rays in the CT scan has the tendency to *ionize* the nylon filaments. Thus, Rexine was the ultimate choice.

V. Calculation

5.1 Wattage of the heat source (Hot air blower):

$$Q = m \times c_p \times \frac{dT}{dt} \quad (1)$$

where,
m – mass
c_p – specific heat of rexine
dT – change in temperature between the top surface and the bottom surface of the rexine
dt – change in time (Time taken to heat the rexine)
Given data,
m= 1kg, c_p=1.3 kJ/kg K, t= 120 s
T_1 = 170 °C
T_2=40°C

So, the wattage requirement is,

$$\dot{Q} = 1 \times 1.3 \times 10^3 \times \left\{\frac{170 - 40}{120}\right\}$$
$$\dot{Q} \approx 1400\ Watts$$

Upon consideration, with respect to efficiency (70%), a 2000W hot blower is used.

5.2 Evaluation Of Power Consumption

According to the Public Health Department of the state of Tamilnadu(8), on an average 2,500 scans are performed by around 50 scan centers across the state. Thus, on average, 50 scans per day in a scan center. The average time is 20 minutes per scan. This implies that the mattress has to function approximately 8 hrs. per day. The power consumed by the mattress per is given by,

Power (in terms of Unit/kWh):

$$P = 2000\ watts\ \times 8hr$$
$$P = 16000\ Wh$$

Thus, the power consumed by the mattress is 16 Units per day

5.3 Heat Transferred from surface to the room

Convective heat transfer:

$$\dot{Q} = \frac{h \times A}{T_s - T_\infty} \quad (2)$$

Where,
h - Convective heat transfer coefficient (W/m^2 °C)
A - Surface area (m^2)
T_s - Surface temperature (°C)
T_∞- Room temperature (°C)

Average temperature:

$$T_f = \frac{T_s + T_\infty}{2} \quad (3)$$

Let,

T_s =40 °C
T_∞ = 22 °C

$$T_f = \frac{40 + 22}{2}$$
$$T_f = 31°C$$

Biot number:

$$B = {}^{1}/_{T_f} \quad (4)$$

$$B = \frac{1}{31}$$
$$B = 3.299 \times 10^{-3} °C^{-1}$$

Properties of air @ 31 °C:
Thermal conductivity (k)= 0.02605 W/m °C
Thermal diffusivity(γ) = 1.59×10^{-4} m^2/s
Prandtl number (Pr)= 0.707
Characteristic length (L_C)= A_S/P
Rayleigh's Number:

$$Ra = \frac{g \times \beta \times (T_s - T_\infty) \times {L_c}^3 \times Pr}{v^2} \tag{5}$$

where,

Ra – Rayleigh's number
g – Acceleration due to gravity
β – Thermal co-efficient of expansion
L_c – Characteristic length
v – Fluid viscosity

$$Ra = \frac{9.81 \times 3.299 \times 10^{-3} \times 18 \times 0.173^3 \times 0.707}{(1.59 \times 10^{-4})^2}$$

$$Ra = 5.98 \times 10^4$$

Nusselt's Number:

$$\mathrm{Nu} = 0.54 \times Ra^{\frac{1}{4}} \tag{6}$$

$$\mathrm{Nu} = 0.54 \times (5.98 \times 10^4)^{\frac{1}{4}}$$

$$Nu = 8.45$$

Co-efficient of heat transfer:

$$h = \frac{(k \times Nu)}{L_c} \tag{7}$$

$$h = \frac{(0.02605 \times 8.45)}{0.1735}$$

$$h = 1.26 \ \frac{W}{m^2} ^\circ\mathrm{C}$$

Convective heat transfer:

$$\dot{Q} = \frac{h \times A}{T_s - T_\infty}$$

$$\dot{Q} = \frac{1.26 \ \times 0.84}{40 - 22}$$

$$\dot{Q} = 19.05 \ W$$

The convective heat transfer was found out to be, 19.05 watts.

5.4 Electricity consumption by Air-Conditioner

The amount of electricity consumed by the air conditioning unit to maintain the overall temperature of the room for approximately 50 patients per day is given by,

$$E = 19W \ \times 20 \ \mathrm{min} \times 50 \ patients/day$$

$$E = 0.316 \ kWh$$

Thus, the extra load on the Air Conditioning system of the Scanning room to maintain the overall temperature of the room constant, is 0.316 Unit per day.

5.5 Total power consumption

The total power consumption of the warm mattress along with the excess power consumed by the air conditioner is given by,

$$P = 16 + 0.316 \ units/day$$

$$P \sim 17 \ units/day$$

VI. Results and Discussion

6.1 Wattage of heating element (Hot air blower): 2000 Watts

The calculation of the power requirement of the hot air blower is carried out based on the temperature requirement that the Rexine has to achieve.

The material property of the Rexine such as thermal conductivity and specific heat and density is taken into account for calculating the amount of power required to achieve the desired temperature on the top surface of the mattress, in a required period of time (response time of the system). Assuming 70% efficiency of the heating element, an overall of 2000 Watts is required to operate the heating element at a steady-state condition.

6.2 Power consumption by warm mattress per day: 16 Units/day

The average power consumed by the warm mattress in a day is calculated based on the approximate estimation of the number of medical imaging centers and hospitals equipped with one, considering the state Tamilnadu as a sample set.

Thus around 50 scans are performed of an average duration of 20 minutes per scan. This translates to 8 hours of operation of the warm mattress in a day, which consumes 2000 W of power. According to this, around 16 Kilowatt-hour, or 16 units of current would be consumed by the mattress.

6.3 The power consumed by the AC: 0.316 Units/day

The superconducting magnets in the MRI machine produce a large amount of heat. To keep the temperature not exceeding the safety limit, liquid helium cryogen is used to remove the excess heat. In case of any cooling system failure or any external reason for an increase in the temperature of the liquid helium will cause its volumetric expansion. Due to this pressure builds up in the coolant container. To prevent the container exploding, the expanding liquid is slowly released into the atmosphere. This safety measure is called Quenching(9). But this is needed to be done slowly or else would prove catastrophic. Thus, maintaining the temperature of the imaging room is very critical. The presence of a heating element in the room, such as the warm mattress, would increase the temperature of the surrounding through convective heat transfer. This puts an additional load on the air-conditioning system of the room. The heat transferred to the surrounding air is calculated using the Natural convection model and assuming steady-state heat transfer.

The power consumed by the air-conditioner to compensate for the increase in temperature of the room due to the warm mattress is estimated to be 0.316 units. The total power consumption due to the presence of the Warm Mattress = (16 + 0.316) units/day

~ 17 Units per day

VII. Conclusion

The thermogenesis responses to the exposure to cold environments such as the involuntary shivering and the formation of brown are the major sources inaccuracy in the medical imaging process. The lower temperatures also cause discomfort and fatigue in patients. In this case, an active aid for providing warmth is essential. But conventional warm mattresses and heat blankets are found not suitable to be used in the imaging room due to safety protocols. Thus, the paper elaborately discusses the procedural steps involved in the designing of a warm mattress which is compatible with the safety guidelines of the imaging room. The metallic heating element is placed apart and far away from the mattress. The heat is then conveyed to the mattress using forced-convective air current. The temperature is monitored and controlled with an active control module depending up on patient's comfort level. The design of the mattress is kept simple to facilitate easy maintenance. The component used in the design is chosen such that it is inexpensive and readily available. This facilitates affordability and easy adoption by the hospitals and scanning centers.

REFERENCES

[1]. Thermogenic adipocytes that control energy and glucose homeostasis. Sidosis, L and kajimura, S. 2015, The Journal of clinical investigation, pp. 478-486.

[2]. Magnetic resonance imaging safety: principles and guidelines. Stikova, E. 2012, Contributions of Macedonian Academy of Sciences & Arts, p. 33.

[3]. Pappas, Stephanie. Man Dies in MRI Accident: How Does This Happen? livescience.com. [Online] January 29, 2018. [Cited: August 07, 2020.] https://www.livescience.com/61558-mri-accident-death.html.

[4]. The investigation of groove geometry effect on heat transfer for internally grooved tubes. Bilen, K, et al. 2009, Applied Thermal Engineering, p. 29.

[5]. Thermal Conductivity of Selected Materials and Gases. www.EngineeringToolBox.com. [Online] [Cited: August 07, 2020.] https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html.

[6]. Indian Ministry of Human Resource Development. Problem Statements. Smart Indian Hackathon. [Online] 2020. https://www.sih.gov.in/sih2020PS.

[7]. Cengel, Yunus and ghajar, Afshin. Heat and Mass Transfer. Newyork : McGraw-Hill Education, 2015. 978-0-07-339818-1.

[8]. Narayan, Pushpa. Now, receive scan reports by email from 3 Tamil Nadu hospita .. Times of India. [Online] Febraury 28, 2018. [Cited: August 07, 2020.] https://timesofindia.indiatimes.com/city/chennai/now-receive-scan-reports-by-email-from-3-tn-hosps/articleshow/63101732.cms.

[9]. Westbrook, C. MRI at a Glance. s.l. : John Wiley & Sons, 2013.

M. Hariharan, et. al. "Design and Development of Novel Warm Mattress for Medical Application."*International Journal of Engineering Science Invention (IJESI)*, Vol. 10(03), 2021, PP 39-46. Journal DOI- 10.35629/6734