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Control of the bed thermal environment by a ventilated mattress

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Abstract. Thermal comfort affects the sleep quality and well-being of people. The effect of a ventilated mattress (VM with integrated localized heating on providing the necessary thermal conditions for comfort in the bed-microenvironment was studied. The VM has an exhaust opening located under the feet of a lying person. Air is sucked and transported inside the mattress by a small fan connected to the mattress. The benefit of using such a mattress is that it sucks and removes body-emitted bio-effluents, which prevents the pollutants to spread in the room. The air movement inside the mattress provides cooling to the body, which makes the bed micro-environment comfortable during the cooling season but may cause discomfort during the heating season. Therefore, the VM was further developed by implementing local heating. Full-scale experiments were performed in a climate chamber furnished with a single bed equipped with the VM. A full-size thermal manikin was used to simulate a person lying in the bed. The performance of the VM with regard to the provided body heating/cooling was studied at room air temperatures of 19, 23, and 28 °C. The control of the thermal conditions in the bed-microenvironment was tested when the VM was operating at different airflow rates and local heating power. A reference condition at 23 °C without the VM in operation was assumed to provide thermal comfort in the bed. The performance of the VM was evaluated based on a comparison of the body dry heat flux from the segments and the whole body of the thermal manikin obtained with the VM in operation and during the reference condition. The results show that it was possible to achieve the same body heat flux at all studied room temperatures using the VM with localized heating as in the reference condition. The use of the VM combined with localized heating with control based on the individual needs of the user can be an efficient method for providing thermal comfort in a bed at a wide range of room air temperature. Energy can be saved by expanded lower and upper room temperature limits recommended in the standards.

Keywords. Bed microenvironment, ventilated mattress, local body heating and cooling, thermal comfort.
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1. Introduction

The indoor environment highly influences the health, productivity, and comfort of the occupants. Therefore, a healthy and comfortable environment is necessary for the quality performance of the occupants. However, there are several sources of pollutants in buildings. Among these pollutants, humans are one of the main sources of bio-effluents that can substantially reduce indoor air quality. In addition, sensory pollution load from people, such as body odour from sweat and the skins' sebaceous secretions, foul breath, and gases from the digestive tract, can be present in the indoor air [1].

Removing pollutants at the source before mixing with the room air is an effective way to reduce the pollutants concentration in the room. An advanced air distribution (AAD) based on providing a personalized microenvironment is a promising solution [2] both for energy saving and higher IAQ. One of the most efficient locations for integrating the local ventilation system is the bed, considering one third of the time we spent sleeping. The AAD solution integrated in a bed can considerably remove air pollution before it is mixed with the room air, thus improving the occupant perceived air quality.

An AAD solution with source control in the bed, named VM (Ventilated Mattress) has been shown to remove effectively polluted air in the bed microenvironment and increase room air quality [3]. Furthermore, the study conducted with a thermal manikin lying on a VM showed that the cooling effect by the movement of air sucked through the mattress can enhance the bed thermal microenvironment and can improve the occupant's thermal comfort in warm indoor environments [4]. However, the study also concluded that the cooling effect of the VM is nonuniform, which can potentially cause thermal discomfort for the occupant, especially during the heating season. In this regard, utilizing a local heating solution for the VM could be beneficial in improving thermal comfort. In this paper, the application of the VM combined with a localized heating method to improve the thermal perception of the human body is examined.

2. Methods

2.1 Experimental Facilities

The experiment was performed in a full-scale test room arranged as a single bedroom of size 4.68 m × 4.7 m × 2.6 m (W × L × H). The room background was ventilated by total volume mixing ventilation. Diffusers for air supply and exhaust were a perforated square diffuser and a circular diffuser, respectively. The diffuser was supplying clean outdoor air in one way as shown in Figure 2-1. A 50 L/s (3 ACH) ventilation rate was set, which is a typical air change rate (ACH) for ventilating general patient rooms in hospitals according to the ASHRAE standard [5].

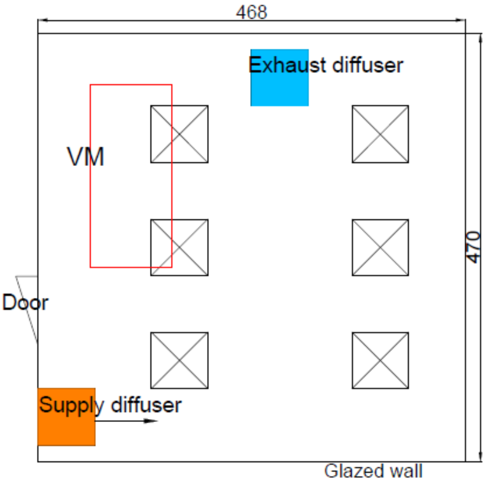

Figure 2-1:Ceiling arrangement with light and diffusers

The VM's was made up of synthetic fiber, which is permeable for air. With the use of an exhaust fan, the air was moved through the VM starting from the exhaust opening at the feet and was taken out from the top of the mattress through exhaust ducts at the left and right sides of the VM, as shown in Figure 2-2. The exhaust opening at the feet was covered with a polyester mesh. An additional, regular mattress of 6 cm thickness was placed below the VM.

Figure 2-2: Ventilated mattress(VM)

A thermal manikin consisting of 23 body segments was used to simulate an occupant in bed. The thermal manikin had the shape of an average Scandinavian female with a height of 1.68 m, weight 22 kg and size 38. During the experiments, so-called Comfort mode in the Manikin software was used to control the surface temperature of manikin segments to be the same as the skin temperature of an average person in the state of thermal comfort [6]. The evaluation of the local cooling effect was conducted using the manikin with different clothing levels, including naked condition, dressed with long sleeve pyjama, short sleeve pyjama, and short pyjama. Two local heating sheets of size 50 cm x 60 cm were used for the study, and the sheets were placed below the feet and below the back, inside the VM below the supporting mesh, as shown in Figure 2-3. One of the local heating sheets was placed below the manikin's feet due to high heat loss at the feet. The local heating sheet below the feet could also heat up the exhaust air flowing through the VM. The second local heating sheet was placed below the back as the back of the manikin had the largest contact area with the VM. The power of each local heating sheet was adjusted using a transformer.

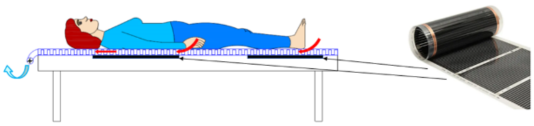

Figure 2-3:Location of the local heating sheet in the VM

In addition, carbon fiber heating elements were placed below the arms to compensate for the high local heat loss, as shown in Figure 2-4. The heating level control of the carbon fiber heating elements was done using an adjustable DC supply.

Figure 2-4:Carbon fiber heating element

The temperature in the room near the bed at 0.6 m and 1.1 m was constantly monitored to verify a stable room temperature (Figure 2 5). The surface temperature of the VM was measured at five different locations, such as below the left and right thigh of the manikin, close to the bottom part, below back, below upper back. Also, the exhaust air temperature was monitored by one sensor placed inside the VM at the exhaust duct.The temperature measurements were recorded every minute using EK-H4 evaluation kit from Sensirion. The digital sensors SHT31 with a measurement accuracy of ±0.2 ℃ can measure the temperature in the range of 0℃ to 90℃. The temperature sensors were attached on the mattress and insulation was used to isolate the sensors from the side exposed to the microenvironment or in contact with manikin's body.

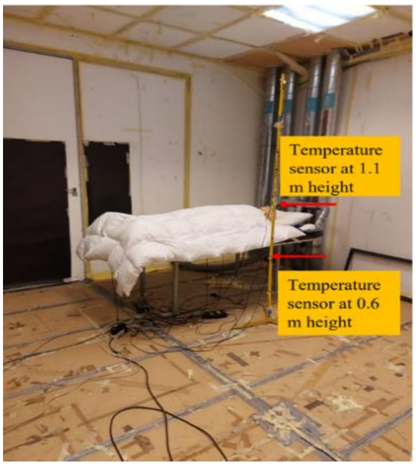

Figure 2-5:Temperature sensors location in the room

The velocity in the room around the bed was measured to ensure the air speed was low around the bed. The air speed around the bed, 20 cm from the bed, was measured using a multichannel low-velocity thermal anemometer AirSpeed 5000, which uses a sensoAnemo 5100SF transducers. The transducer was equipped with a probe that includes omnidirectional air speed and temperature sensors. The range of air speed measurement by the sensor was 0.05 m/s to 3 m/s with an accuracy of ±0.02 m/s ± 1%.

2.2 Experimental Conditions

Various standards define comfortable indoor temperatures. For instance, according to the ASHRAE standard [5], the ideal temperature for thermal comfort in a general patient room is 20°C - 24°C. According to the Danish standard DS/ISO/TR 17772-:2018 [7] for bedrooms in residential buildings with indoor environmental quality (IEQ) of category I and II, the recommended design values of the indoor operative temperature in winter and summer are 21°C (for winter, IEQ I), 25.5°C (for summer IEQ I), and 20°C (for winter, IEQ II) and 26°C (for summer, IEQ II) respectively. In this regard, a room temperature of 23°C was assumed to be thermally acceptable for the person lying down naked. Therefore, a naked manikin covered with a 600 g duvet without using VM at a room temperature of 23°C was chosen to be the reference case in this study.

A summer period with a room temperature of 28°C ±0.5°C and a winter period with a room temperature of 19°C ±0.5°C were considered in the experiment. The winter and summer room temperatures were chosen to be slightly below and over the minimum and maximum standard values of 20^{o}C and 26^{o}C (IEQ II) [8]. It was hypothesized that the VM can provide thermal comfort at extended lower and upper room temperature limits than the recommended in the standard DS/ISO/TR 17772. Extending the room temperature range is a well-known strategy to achieve energy savings in buildings [9] [10]. Clothing and bedding for the manikin was adapted to different room conditions. For instance, a 600 g down duvet was utilized at 23°C room temperature condition, whereas, a thicker 1055 g down duvet was used for the case simulating winter conditions (19°C) and a thin cotton sheet was used during the summer conditions (28°C). The manikin was placed in a supine position, with a pillow for a headrest. At room temperatures of 19^{o}C and 23^{o}C, the manikin was clothed with long sleeve pajamas and short sleeve pajamas respectively. A short pajama including a singlet and shorts was used during the conditions at 28^{o}C. At the three room temperatures (19°C, 23°C, 28°C), experiments were performed at an exhaust flow rate of 1.5 L/s, 3 L/s, 4.5 L/s, 6 L/s, and 10 L/s without local heating and 3 L/s exhaust flow rate (optimum to remove bioeffluents) with local heating.

2.3 Experimental Procedure and Data analysis

The room ventilation system and the manikin were both operational at all times to maintain a steady room air temperature. After the temperature reached steady state, the measurements were started. Firstly, the air velocity in the room around the bed was measured to ensure that the air speed around the bed was less than 0.1 m/s. At the beginning of experiments, the temperature in the room was set to 23°C, which was the reference condition. For each of the performed experiments (referred in the following as cases) the segmental and whole-body cooling effect on the manikin was assessed by comparing the manikin's segmental heat flux data obtained from the particular experimental condition with that of the reference case (at 23°C, naked manikin, no VM). If the heat flux of the segments was higher than the heat flux of the respective segments in the reference case, the local heating was provided for compensation. The local heating power was adjusted using a transformer to reduce the body heat flux and make it closer to the reference case.

During the whole experiment, the temperature below the manikin's left and right thighs, close to the bottom part, below the back, below the upper back as well as the exhaust air temperature were measured. Furthermore, the power required for the local heating elements were recorded.

2.3.1 Data analysis

The average of the logged dry heat flux was calculated for a ten minutes interval after the manikin reached a steady state. The cooling effect of the VM was evaluated by comparing the data of the average dry heat flux obtained for each body segment for the cases with a different exhaust flow rate of the VM against the reference case data. The difference between the average dry heat flux of each body segment and the average heat flux obtained in the reference case of the respective body segment (designated as ΔQ) was calculated first. ΔQ was used to define ΔQmax. Where ΔQmax of the measured case is the maximum value of the differences ΔQ for each body segments. It was assumed in this study that for an acceptable thermal environment, the difference between the average heat flux of the manikin during a case with VM turned ON and the reference case without VM should be less than 6 W. That is, the condition for the acceptable thermal environment is defined as

$$\Delta Q_{max} < 6W \qquad (1)$$

3. Results

The measured heat flux at the reference case is shown in Figure-3-1. The differences in the heat flux of the various body segments was due to the difference in the thermal insulatilon for each body segments. For example, the heat flux of the body parts in contact with the duvet (pelvis, chest, front things) was lower compared to the other body parts. The heat flux measured at 23 °C with the VM in operation for the cases with different exhaust airflow rate are shown in Figure 3-2. For every case, the average dry heat flux of the body segments of the undressed manikin measured at the studied exhaust airflow rates of the mattress - 1.5 L/s, 3 L/s, 4.5 L/s, and 6 L/s - was compared with the average dry heat flux at the reference case without the VM.

Figure 3-2 depicts the ΔQ for different exhaust flow rates of the VM at 23°C room temperature. It can be seen that the average dry heat flux of the manikin's body segments increased as the exhaust airflow rate increased, which demonstrates the cooling effect introduced due to the airflow of the VM. It can also be seen from Figure 3-2 that ΔQ is more substantial at certain body segments, especially at the lower segments of the body and the body segments in contact with the mattress, namely backside, arms, feet, legs, and back. A nonuniform ΔQ across the body segments suggests potential risk of local thermal discomfort.

Similarly, the same trend was observed at 19°C room temperature at the studied exhaust airflow rates of the VM. The results are shown in Figure 3-3. The surface temperature of the mattress at the studied exhaust flow rates at 19°C is shown in Figure 3-4. The results are in agreement with the results of the local cooling effect and nonuniform heat flux loss from the body segments. The highest temperature deviation from the reference case temperature occurred below the back, below the left thigh, and close to the bottom part. The temperature difference and heat flux below the left thigh were different than the one below the right thigh. Such a difference is possibly due to asymmetry in the airflow of the VM or asymmetrical contact of the respective body segments with the VM. An attempt to eliminate the local cooling effect of the VM by utilizing local heating was applied (shown in Figure 2-3). The objective of the local heating method was to make the heat flux of the different manikin body segments closer to the heat flux in the reference case and meet the defined acceptable thermal environment criteria given by equation (1). Heating

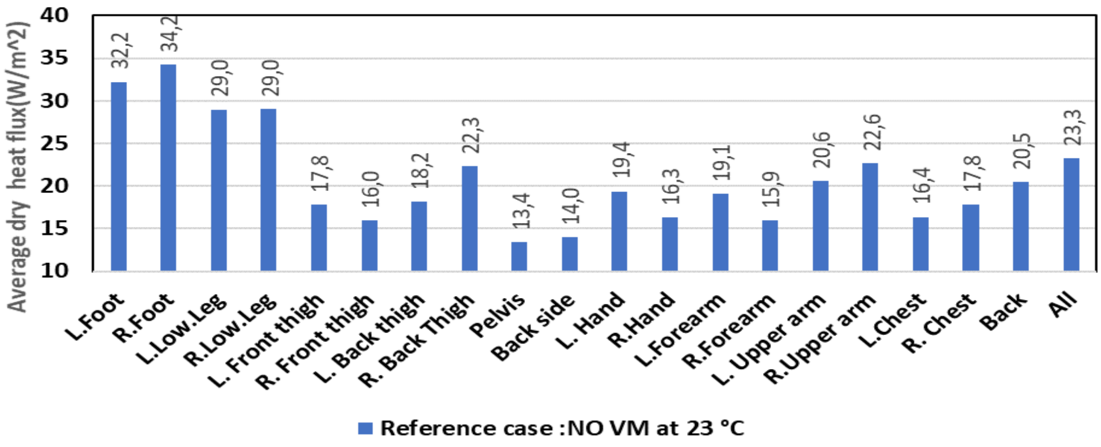

Figure-3-1: Manikin's average dry heat loss at reference case

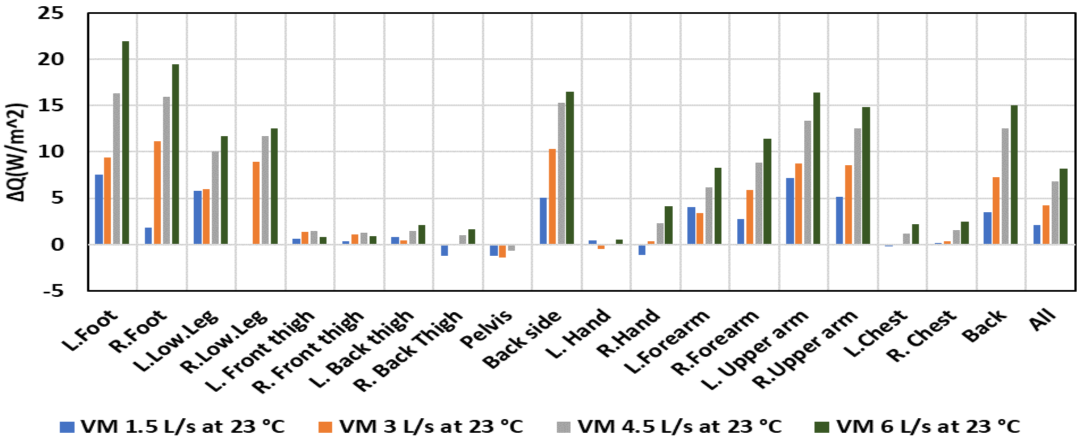

Figure 3-2:Average dry heat flux for different exhaust flow rates of the VM at 23 ºC

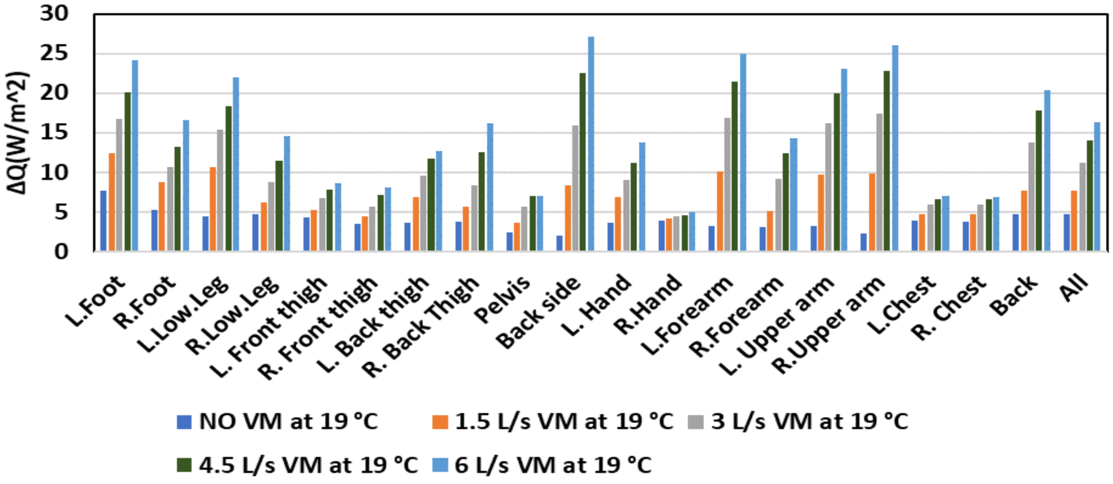

Figure 3-3:Average dry heat flux for different exhaust flow rates of the VM at 19 ºC

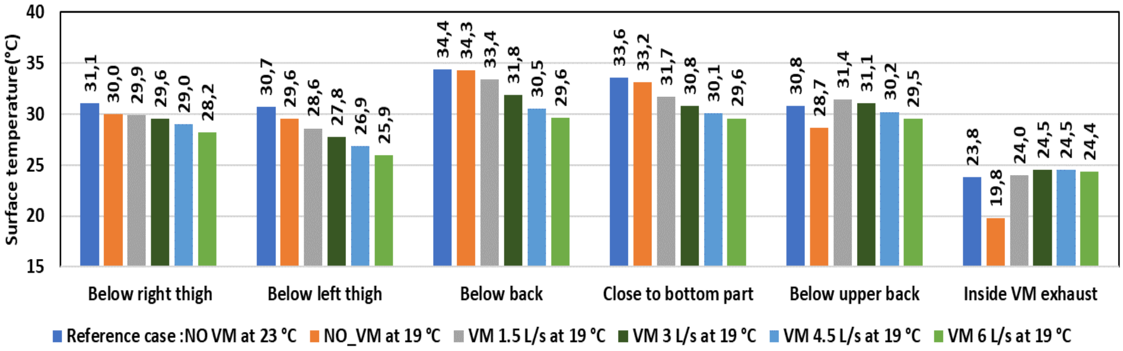

Figure 3-4:Surface temperature at different exhaust flow rate at 19ºC

compensation was carried out for the VM operating at 23ºC and at 3 L/s exhaust. After multiple iterations by adjusting the heating levels, the 8 Watts heating at the feet and 9 Watts at the back was the most optimal choice. The results in this case are shown in Figure 3-5. It can be seen that it is possible to make the heat flux of different manikin body segments closer to the heat flux in the reference case when local heating is applied. Furthermore, it was found out that by dressing the manikin with a long sleeve pajama and with added insulation on top of the mattress, no extra local heating was required to compensate for the heat loss (Figure 3-5, bars in orange). However, for both cases in Figure 3-5, the heat flux at the arms was higher than the maximum acceptable deviation (ΔQmax) from the reference case and still needed to be adjusted. Thus, the Carbon fiber heating method was required below the arms to provide the necessary heat to the arms.

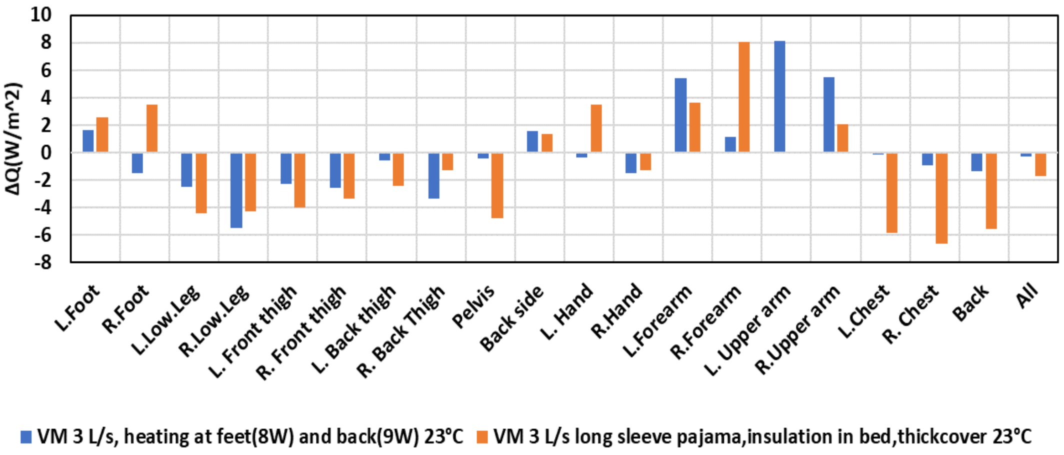

Figure 3-5: Heating compensation at 3 L/s VM case at 23°C

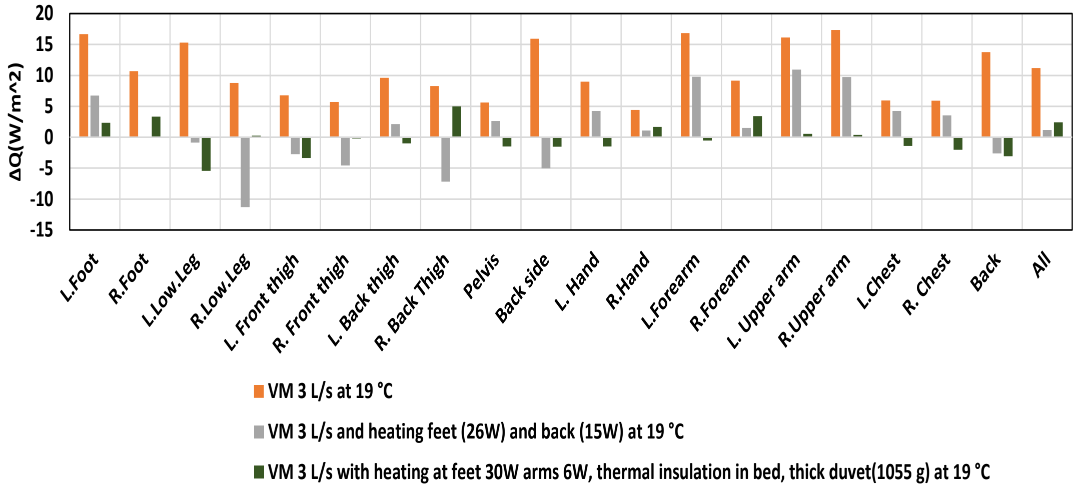

Figure 3-6: Heating compensation at 3 L/s VM case at 19°C

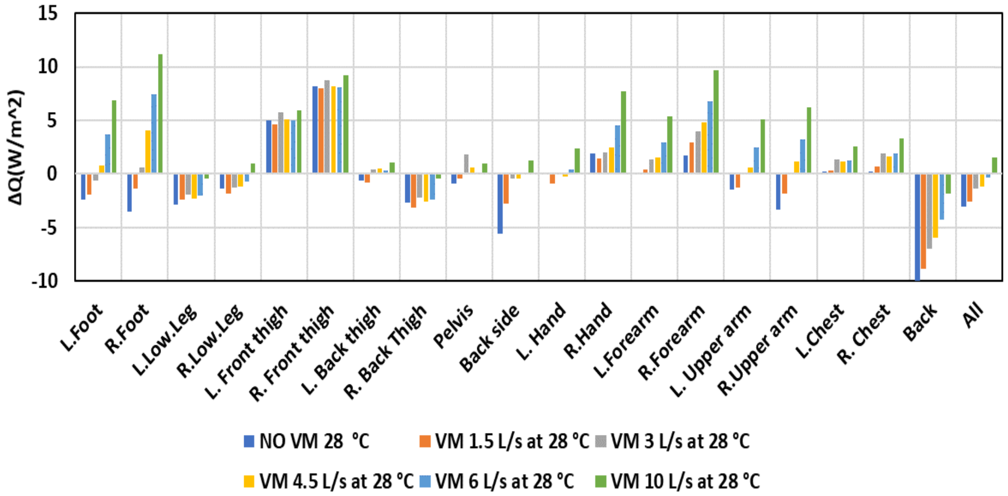

Figure 3-7:Average dry heat flux for different exhaust flow rates of the VM at 28 °C

Figure 3-6 depicts the local heat flux of the body segments for the case of 3 L/s exhaust flow rate of the VM with the local heating sheet (as shown in Figure 2-3) at 19°C room temperature. The results indicate that it is possible to use the VM at 3 L/s exhaust flow rate at 19°C room temperature and mitigate the cooling effect of the VM for all body parts except at arms when providing local heating of 26 W at the feet and 15 W at the back. In addition, the ΔQ for the right low leg was greater than 6 W, i.e. the acceptable range considered. This measurement could be a possible outlier due to unwanted infiltration from the room due to the air gap between the duvet and the VM. Excluding the arms and the outlier, the ΔQmax was less than 6 W, i.e., in the range of the defined acceptable thermal condition for this study. To compensate for the heat loss at the arms, a carbon fiber heating element, as shown in Figure 2-4, was placed below both arms along with the thermal insulation on top of the VM and the local heating sheet below the feet. The experiments were then repeated with the local heating sheet, and the result of the heat flux at the arms is shown in the Figure 3-6. It can be seen that using the local heating sheet and the carbon fiber heating element below the arms can effectively compensate for the heat loss due to the VM.

Figure 3-7 shows the average dry heat flux of the manikin's body segements with the VM in operation at 28°C room temperature. The manikin was dressed with short pajama and covered with a thin sheet. Similar to the other room temperatures, the cooling effect of the VM at 1.5 L/s, 3 L/s, 4.5 L/s, 6 L/s, and 10 L/s exhaust flow rate of the VM at 28°C room temperature were assessed. It can be seen that the VM operating at 3 L/s can provide a cooling effect which can reduce substantially the difference in the heat flux with the reference case (ΔQ).

4. Discussion

The experimental results showed that the dry heat flux from the body segments of the manikin increases with the exhaust flow rate of the VM at all studied room temperatures. The heat flux was higher with a higher exhaust flow rate because a higher exhaust flow rate means more air in the bed microenvironment is displaced with cooler ambient room air at a higher velocity, thus increasing the convective heat transfer. The suction of the VM continuously displaces the air in the bed microenvironment, and it was replaced by the air under the cover at ambient temperature, which was lower than the manikin segment temperature. This difference in temperature coupled with the airflow leads to increased heat transfer by convection between the manikin and air in the bed microenvironment.

In addition, higher airflow rate through the VM also means that the mattress's effective thermal insulation was reduced, increasing conductive heat loss in the body segments in contact with the mattress. The measured surface temperature of the VM also decreased with an increase of the exhaust flow rate through the VM. The largest drop in surface temperature with respect to increasing the VM's exhaust flow rate was observed below the back of the manikin and close to the bottom part. As explained, these body segments are firmly in contact with the VM. Thus, the drop in surface temperature also implies that the heat flux of these body segments are primarily due to conduction.

The different body segments of the manikin were exposed to nonuniform cooling in the bed, leading to different heat flux loss. Even inside the bed microenvironment, which was covered with a duvet, there were differences in the heat loss of the body segments. For example, the chest, pelvis, and front thigh were in contact with the duvet, and heat loss occured by convection to the air below the duvet and conductive heat loss to the duvet. The backside, back, and back thigh were firmly in contact with the mattress; hence conductive heat loss to the mattress was dominant. However, some areas of these segments may not be in contact with the mattress, therefore, convection heat loss for these areas occured. On the other hand, feet, legs, and arms had a larger exposure to the airflow in the bed microenvironment, thus has a high convective heat loss and limited conductive heat loss. In addition, using thermal insulation, the conduction heat loss through the VM can be reduced, but still there was a non-uniform heat loss, particularly in the arms.

The VM cooling effect can be beneficial during summer temperatures (28°C). With an increased exhaust flow rate of the VM, it is possible to increase the heat loss from the manikin's body segments.

This paper demonstrates the possibility of using local heating to improve the occupant's thermal comfort with the VM. With the local heating solutions employed in this paper, the temperature difference between the body and the surface of the VM was reduced, resulting in decreased heat loss from the body. An increase in the surface temperature of the VM in contact with the manikin segment with local heating can directly compensate for the conductive heat loss. However, compensating with the local heating was more challenging for body segments with primarily convective heat loss, which are not in firm contact with the VM, such as arms and feet.

The key function of the VM is pollution (body bio-effluents) source control which results in improved room air quality and energy reduction. To that end, it could be beneficial to explore changes in VM design that can reduce the undesired cooling effect in winter and thereby reduce the local heating while ensuring source control. One option could be to change the exhaust connection location during winter. For instance, if the exhaust connection location is placed exactly below the suction opening of the VM instead of being at the opposite end of the mattress near the head, it is possible to limit the cooling effect at upper body parts because there is no air movement through the VM.

Finally, the study presented in the paper is performed on a specific configuration of the VM with a manikin lying in the supine position. Thus, the study is limited when deriving general conclusions about the VM. Also, only one position of the manikin was tested, but in reality, people lying on the bed have different positions. Therefore, the cooling effect of the VM and the effectiveness of the local heating with different positions of the lying person can also be verified during the human subject experiment.

5. Conclusion

The potential local thermal discomfort for the occupant due to cooling effect induced by the air movement in the VM is addressed in the paper. In addition, a localized heating method is suggested to improve the thermal perception of the human body. The key conclusions of the study are:

- The body segments where the local cooling is critical are the feet, back, and arms. This discomfortable cooling effect can be eliminated by the studied local heating methods;
- At 23°C room temperature, the local heating can compensate the local cooling at the studied flow rate (3 L/s) through the mattress. However, with the addition of thermal insulation on top of the VM, the local cooling effect can be reduced. Even though local heating below the arms is required to eliminate the nonuniform cooling effect;
- At 19°C room temperature, the addition of thermal insulation on top of the VM reduced the need for local heating. However, local heating at the feet was necessary to obtain thermal comfort;
- At 28°C room temperature, the cooling effect of the VM can be beneficial to obtain thermal comfort for the occupant in bed. It is observed that no local heating was needed to compensate the cooling effect of the VM.

6. Acknowledgement

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References

[1] P. Wargocki, «Sensory pollution sources in buildings,» *Indoor air,* vol. 14, pp. 82-91, 2004.

[2] A. K. Melikov, «Advanced air distribution: improving health and comfort while reducing energy use,» *Indoor air*, vol. 26, pp. 112--124, 2016.

[3] M. P. Bivolarova, A. K. Melikov, C. Mizutani, K. Kajiwara Z. D. Bolashikov, «Bed-integrated local exhaust ventilation system combined with local air cleaning for improved IAQ in hospital patient rooms,» *BAE*, vol. 100, pp. 10-18, 2016.

[4] M. P. Bivolarova, A. K. Melikov, M. Kokora e Z. D. Bolashikov, «Local cooling of the human body using ventilated mattress in hospitals,» in *Proceedings of the 13th International Conference on Air Distribution in Rooms-Roomvent*, 2014.

[5] A. N. S. I. ASHRAE, *ASHRAE/ASHE Standard 170-2008 Ventilation of health care facilities,* Atlanta, 2008.

[6] Manikin – manual, «pt-teknik.dk/files/manual.pdf,» [Online]. Available: http://pt-teknik.dk/files/manual.pdf. Accessed 29 03 2022.

[7] Danish Standards Association, «DS/ISO/TR 17772-2:2018 Energy performance of buildings -- Overall energy performance assessment procedures -- Part 2: Guideline for using indoor environmental input parameters for the design and assessment of energy performance of buildings,» 2018.

[8] Danish Standards Association, «DS/EN ISO 7730 Ergonomics of the thermal environment –Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria,» 2006.

[9] J. Khodakarami e I. Knight, «Thermal comfort requirements in Iranian hospitals,» in *Citeseer*, 2007.

[10] R.-L. Hwang, T.-P. Lin, M.-J. Cheng e J.-H. Chien, «Patient thermal comfort requirement for hospital environments in Taiwan,» *Building and environment*, vol. 42, pp. 2980--2987, 2007.

[11] «long infrared underfloor heating film building material,» [Online]. Available: https://www.banggood.com/da/50CMX2M-220V-Far-Infrared-Floor-Heating-Film-Building-Material.

[12] T. Hoyt, K. H. Lee, H. Zhang, E. Arens e T. Webster, «Energy savings from extended air temperature setpoints and reductions in room air mixing,» *hoyt2005energy*, 2005.

[13] S. Schiavon e A. K. Melikov, «Energy-saving strategies with personalized ventilation in cold climates,» *Energy and Buildings*, vol. 41, pp. 543-550, 2009.

[14] « DSF/FprCEN/TR 16244 Ventilation for hospitals,» 2011.