Control of the bed thermal environment by a ventilated mattress: human subject response

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Abstract. Bioeffluents emitted from person lying down in bed can be removed by ventilated mattress (VM) before mixing with the room air. VM is designed to suck air through an exhaust opening located near the feet and move the sucked air inside the mattress. The air moves through the whole mattress and is removed to the exhaust or cleaned and discharged back to the room. The VM can change the thermal conditions in the bed micro-environment and provide uncomfortable local cooling of the person in the bed. Therefore, the design of the ventilated mattress is further improved by incorporating local heating. The response of people to the bed thermal environment generated by the mattress was studied at three room air temperatures – 19°C, 23°C and 28°C. 30 human subjects (15 males, 15 females) of age 20 - 29 years old and body mass index in the range 18 - 27 were exposed to the bed thermal environment provided by the VM. The subjects were covered with a thin duvet (2.9 clo) at room temperature 19°C, a double cotton sheet at 23°C and a single cotton sheet was used at 28°C. The subjects were dressed with pajama (short-sleeve shirt, shorts) and underwear. Thermal sensation assessment was collected through standardized questionnaires. The subjects answered questions regarding their whole body thermal sensation and local thermal sensation of separate body parts including face, head, neck, chest, back, arms, hands, thighs, lower legs, and feet. The bed thermal micro-environment was adjusted by the exhaust flow rate through the ventilated mattress and the localized heating depending on the acceptability of the subjects' thermal sensation collected every 7 minutes. The results show that the applied control of the bed thermal environment increased the acceptability of the whole body thermal sensation votes and the risk of local cold discomfort (especially on the feet and hands) decreased over time. Local heating at the feet will be needed to achieve thermal comfort in room temperatures below 23°C. Local heating incorporated in the VM or separate and the airflow through the mattress can be controlled based on physiological signals of the person's body.

Keywords. Ventilated mattress, bed thermal environment, thermal sensation, thermal acceptability, physiological parameters.
DOI: https://doi.org/10.34641/clima.2022.415

1. Introduction

Thermal comfort is a critical factor that effects sleep quality [1]. A good bed micro-environment can ensure high sleep quality, which directly affects the daytime productivity and mental state of people. In addition, the bed is one of the places where people may stay for a long time, especially in healthcare facilities. An important factor affecting the bed micro-environment is the various airborne odorous contaminants (bio-effluents) emitted from lying people's bodies. These pollutants are difficult to remove by room background ventilation before they mixed with the air near the bed [2].

The main method to solve the pollution problem in the bed micro-environment is by source control. For this purpose, a ventilated mattress (VM) was designed to remove body-emitted pollutants by sucking a small amount of air near the feet of a lying person [2]. A detailed description of the VM can be found in [2]. Although the VM is highly efficient to remove body bio-effluents, it has been found that its design may cause local cold discomfort to the users [3]. Bivolarova et al. [3] found out local body cooling of a thermal manikin's body segments in contact with the surface of the VM. It was concluded that large differences in the body local thermal sensation might be expected when the VM is used. Therefore, human subject experiments are needed to identify the effect

Tab. 1 - The interquartile range (IQR) and median of the age, height, weight and BMI of the subjects.

Gender	Number	Age(year)	Height(cm)	Weight(kg)	BMI(kg/m2)
		Median(IQR)	Median(IQR)	Median(IQR)	Median(IQR)
Male	15	25(22-27)	175(172-178)	72(66-75)	22.3(19.9-22.59)
Female	15	25(23-27)	168(165-170)	57(55-65)	21.5(21.59-24.2)
Total	30	25(23-27)	171(168-175)	65(56-72)	22.0(20.31-23.96)

of the non-uniformity in the local body cooling on the overall thermal sensation of people. There are no relevant studies until now related to the risk of local cold discomfort of people using the VM. The ventilated mattress is a similar system to a personalized environment control system (PECS), aimed to maintain good inhaled air quality and preferred thermal comfort of users [4]. Previous studies on PECS have shown the need for more flexible and sensitive control strategies [5, 6]. To save energy, the overall building temperature is usually set lower in winter and higher in summer when PECS are used [7]. This suggests that people need extra personalized heating or cooling system (radiant heater, fan, personalized ventilation) to reach the individual comfort level. There are some automatic control systems based on time or motion sensors used with PECS, but manual control is still the most accepted method. Compared with the traditional HVAC control systems, people are more willing to spend personal time to control PECS in order to obtain preferred individual micro-environment. Gao et al. (2013) designed a smart system that considers the individual thermal preference and can balance energy conservation with personal thermal comfort in an office environment (SPOT) according to the Predicted Mean Vote (PMV) model of ISO 770 standard [8]. Kim et al. [9] predicted individuals' thermal preference using occupant heating and cooling behaviour and machine learning. Zhu et al. [10] produced an occupant-centric air-conditioning system for recognition and control of thermal preference in the personal micro-environment. These previous studies discussed the application of several control logics for personal comfort systems in office environments where people are mostly sitting. The control of the bed thermal microenvironment generated by the VM is different and has not been analysed so far.

The aim of this study was to investigate the performance of the ventilated mattress combined with local heating for providing thermal comfort in bed. For this purpose, the thermal sensation and acceptability response of thirty subjects was studied. The bed thermal micro-environment (BTME) was adjusted by manually controlling the exhaust airflow rate of the ventilated mattress and the local heating based on the acceptability votes of the subjects' thermal sensation. This study adds new knowledge of the control strategies of the bed thermal microenvironment.

2. Methodology

2.1 Human subjects

In this study, thirty young and healthy human subjects were recruited. The subjects were asked not to drink alcohol and caffeine drinks prior to the experiment and to be rested on the days of the experiment. The experimental procedure and subjective questionnaires were explained to the subjects in advanced. During the experiment, they were wearing pajamas consisting of short-sleeve shirt (0.17 clo) and shorts (0.06 clo) and underwear (0.03 clo (women), 0.04 clo (men)). The basic physical characteristics of the subjects are shown in Table 1.

2.2 Experimental facilities and Measurements

A typical bedroom environment was simulated in a climate chamber with dimensions of 4.7 m × 4.7 m × 2.6 m (W×L×H). The room was ventilated with three air changes per hour of clean air supplied and exhausted by ceiling mounted diffusers. The air was distributed in a way that the air speed in the occupied zone was less than 0.1 m/s. The chamber was arranged to resemble a bedroom. A bed (1.6 m wide and 2 m long) with six cm thick mattress was used. On top of the regular bed mattress, it was placed the ventilated mattress (Fig. 1). Air temperature and relative humidity were measured in the room close to the bed at 0.8 m and 1.2 m above the floor. In addition, the air temperature and relative humidity were measured under the cover around the lying subject at three locations – between the feet, between the thighs and between the torso and the right arm.

The skin temperature was measured at 10 points: forehead, right scapula, left upper chest, right upper arm, left lower arm, left hand, right anterior thigh, left calf, right instep, and left instep. The equipment used in this experiment is shown in Table 2.

The continuous ASHRAE seven-point scale was used to assess the overall and local body thermal sensation including the body parts face, top of the head, neck, chest, back, arms, hands, thighs, lower legs, and feet [11]. The thermal sensation scale was from "cold" to "hot", where hot = +3, warm = +2,

Tab. 2 - Environmental and physiological parameter measuring equipment.

Parameters	Instruments	Accuracy
Air temperature	Sensirion EK-H4 kit, SHT31 sensor	±0.2°C (5°C – 60 °C)
Air humidity		±3% (20 %RH – 80 %RH)
Skin temperature	ibutton DS1922T	±0.5°C (20 -70°C)

slightly warm = +1, neutral = 0, slightly cool = -1, cool = -2, and cold = -3. Acceptability of the thermal sensation was assessed using the acceptability scale. The acceptability scale consists of two continuous scales (Fig.3 right scale) from "clearly unacceptable = -1" until just "unacceptable = -0.01" and from "just acceptable = +0.01" until "clearly acceptable = +1". Each question was shown on a flat screen hanged from the ceiling in front of the bed, on which the subjects were able to see the question and provide their answer.

2.3 Experimental procedure and conditions

The subjects were exposed to three room air temperatures: 19°C, 23°C and 28°C. The relative humidity in the chamber was not controlled. It was in the range of 35 - 50% during all experimental sessions. Each subject participated in three experimental sessions. One session lasted 2 hours as shown in Fig. 2. Each participated in all three sessions at the same time of the day. After entering the chamber, the subject changed clothes, attached the ten skin temperature sensors, and their body parameters (weight, body fat, bone mass, body water, muscle mass physique rating, BMR, metabolic age, visceral fat) were measured on a digital scale before going to the bed to start the acclimation period. During the acclimatization period, the subject adopted a comfortable position, and answer the first questionnaire (Q1) regarding how many hours they slept during the previous night. Afterwards, the temperature sensors for measuring in the bed were placed, as shown in Fig. 1, and the subject was covered up to his/her neck. Most subjects kept their arms below the cover. Only few subjects put their arms above the cover during the session at 28°C. The subjects were covered with a thin duvet (2.9 clo) at 19°C. A double cotton sheet was used at 23°C and a single cotton sheet was used at 28°C. Only one female subject requested to be covered with a blanket on top of the double cotton sheet at 23°C. The thermal insulation of the blanket was 0.65 clo. After the acclimatization period, the ventilated mattress was started at 3 L/s (amount of air exhausted through the mattress). Since, the VM suction openings were at the feet some subjects were experiencing local cooling at their feet. In that case, a small heated mat was placed on top of the feet over the cover until the subject needed it. If a subject was feeling warm, then the flow rate of the VM was increased. The flow rate of the VM at 19°C and 23°C varied for each subject between 3 L/s – 6.5 L/s and at 28°C between 3 L/s – 19.5 L/s.

The subjects were asked to lay only on their backs, and they were allowed to move.

During the exposure time in the bed, the subjects were asked every 10 min to answer the second questionnaire (Q2) regarding their thermal sensation and acceptability. The flow rate and heating power of the local heating device were adjusted every 10 min according to the human subjects thermal preferences.

Fig. 1 - View of a subject lying on the VM and the three temperature sensors positioned around the subject (placed inside green protectors). The white surfaces near the feet are where the suction openings of the VM were.

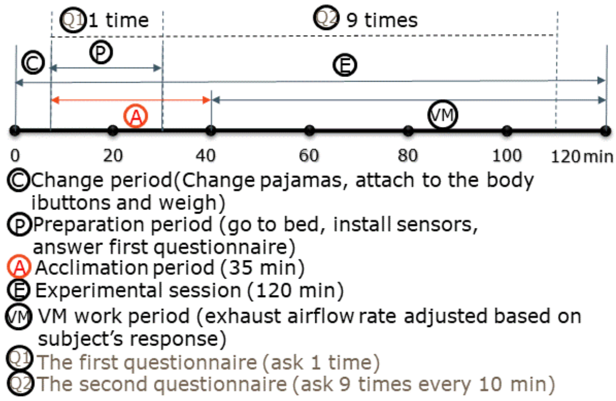

Fig. 2 - Experiment procedure.

2.4 Data Analyses

A total of 90 experiments were conducted with 30 subjects, 830 questionnaires were answered, and 27390 votes were obtained to ensure the statistical significance of the data. Statistical analyses were performed using SPSS version 24.0 for Windows (SPSS Inc., Chicago, IL, USA). The box plots were made to show the results from the overall thermal sensation and acceptability at the three studied room temperatures. The sum of the thermal sensation votes (TSVs) of the subjects were used to show the effect of the VM's control on whether it is effective to provide subjects with acceptable thermal sensation. The following equation was used to calculate the sum of the thermal sensation votes separately for the fifteen female participants and the fifteen male participants:

$$Y_i = \sum_{k=1}^{15} X_{k,i} \qquad (1)$$

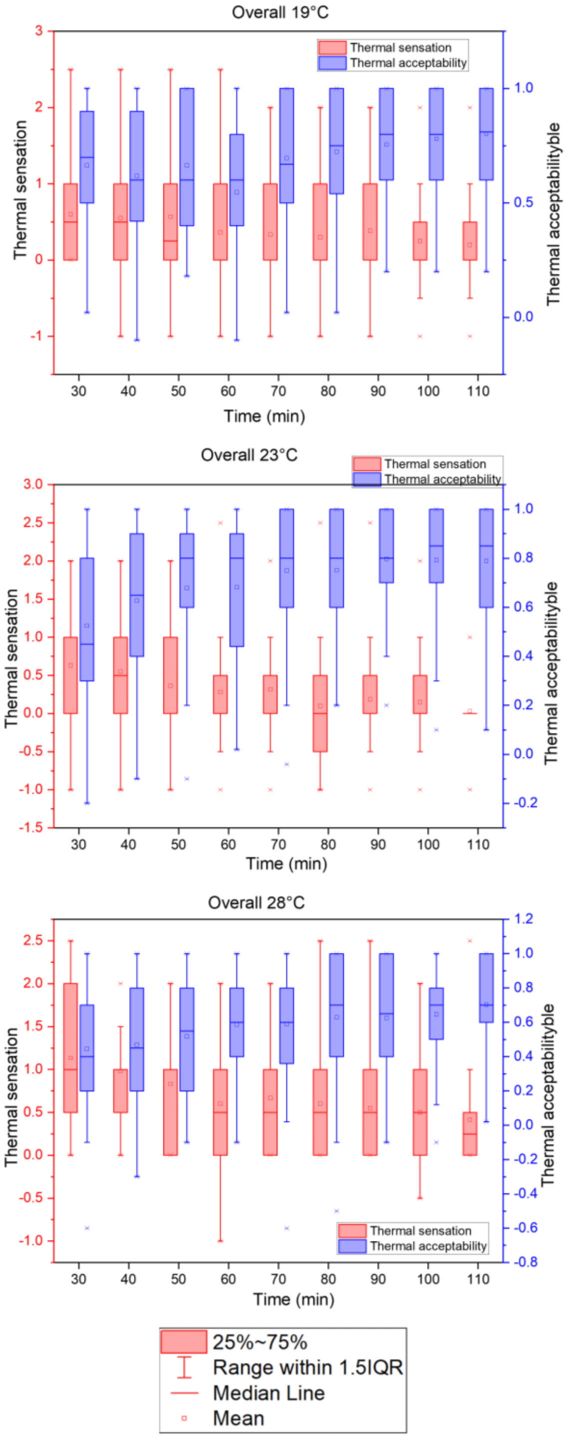

Fig. 3 - The distribution of the overall thermal sensation and acceptability votes of the 30 subjects as a function of the exposure time in the bed at room air temperature 19°C, 23°C, and 28°C.

Where $X_{k,i}$ is the overall or separate body part thermal sensation vote of a subject at the time *i* of answering the questionnaire Q2.

3. Results

The distribution of the overall thermal sensation and acceptability votes of all 30 subjects is shown in Fig. 3 for each experimental room condition. According to the medians and mean values, the thermal acceptability gradually approached almost 1 (clearly acceptable) at the end of the exposure time as the thermal sensation approached almost neutral sensation (equal to 0). This trend can be observed for the three studied room air temperatures. Overall, during the whole exposure time of all experimental conditions the subjects' acceptability of the overall thermal sensation was above just acceptable. These results suggest that the ventilated mattresses combined with local heating can effectively control the bed thermal microenvironment.The fastest increase of thermal acceptability of the subjects was achieved (after 20 min) in the neutral room temperature environment (23°C), where the subjects thermal sensation was between neutral and slightly warm. This means that the bed microenvironment's control may face more challenges when the indoor temperature is cold (19°C) or hot (28°C) than when the room conditions are within the comfortable range (21 - 24°C). Therefore, focus not only on the subjective response but also on the response of the users' physiological parameters such as skin temperature is needed. In this way the time response of the bed microenvironment to meet the users' thermal preferences can be determined.

Fig. 4 shows the sum of the TSVs for the whole body (overall) and different body parts of the participants as a function of time. Fig. 4 shows the separate results for female and male subjects obtained at all three room conditions (19°C, 23°C and 28°C). The overall thermal sensation as well as thermal sensation of the back, arms, thighs, and feet always approached zero at the end of the exposure time in the bed with VM working. This trend is observed for both men and women's thermal sensation. This means that the control of the VM and the local heating at the feet was effective, and the thermal sensation tended to be neutral (equal to zero in Fig. 4). The results for the thermal sensation for the body parts top of head, face, chest, hands, and lower legs showed the same trend of reaching almost neutral thermal sensation at the end of the experimental session. Fig. 4 shows also that the overall thermal sensation of the women was lower than that of the men; especially the differences were large at 19°C. Similar results can be observed for the individual body parts. It was found out that the sum of TSVs for the face of the women were lower than 0 during the entire exposure time at 19°C. The sum of the TSVs of the women in the last 10 min of the exposure time were less than 0 for the arms and feet at 23°C. Whereas, for the men only the thermal sensation at the feet was less than 0 in the beginning and at the end of the exposure at 19°C and at the end of the exposure time at 23°C. The sum of the overall thermal sensation votes and the neck for both the men and the women were higher than 0 during the three studied room temperatures. But a trend moving towards 0 from the start of the exposure until the end of the exposure time can be observed. Furthermore, the sum of TSVs of the body parts in contact with the VM (back, arms, thighs, and lower legs) were higher than neutral throughout the exposure time in the bed at all three room conditions. But due to the VM's cooling effect, the TSVs

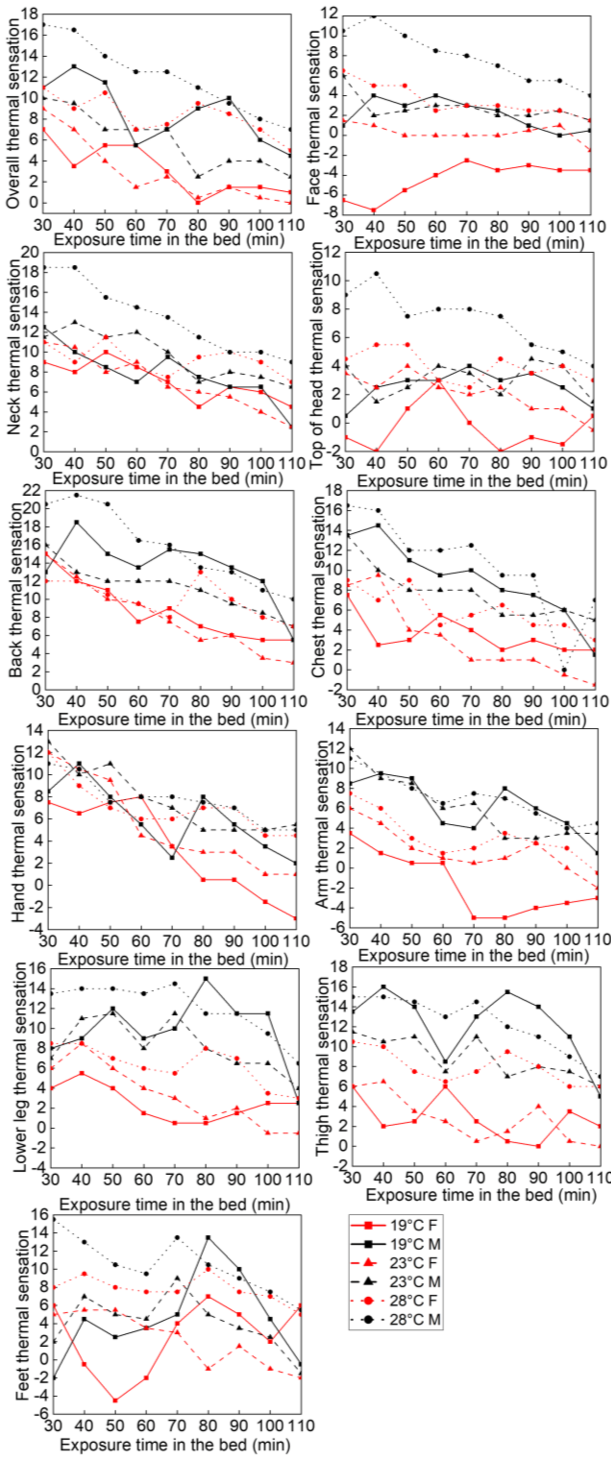

Fig. 4 - Subjects' overall and body parts thermal sensation as a function of time at room air temperature of 19°C, 23°C and 28°C, where F = female and M = male.

approached neutral at the end of the exposure, which proves that the application of the VM has a positive effect to create neutral BTME. The higher TSV for the neck may cause local hot thermal discomfort, but the resulting cooling of the body parts in contact with the mattress seems to be able to reduce this discomfort.

4. Discussion

In this study, the BTME was adjusted according to the feedback of the subjects, which was collected by questionnaires. The whole experiment process was in a state of variable conditions, and the subjects were almost exposed to a neutral micro-environment all the time. This study aims at creating a comfortable BTME for people as much as possible. This study proves the necessity of real-time control of the VM based on the response of the user for creating comfortable BTME. The ultimate goal of control is to integrate an intelligent control of the VM, which requires the VM to recognize the comfort needs of the occupants and adjust its flow rate and surface temperature in time. Therefore, focus not only on the subjective response but also on the users' physiological parameters such as skin temperature is needed. In this way, the time response of the bed microenvironment to meet the users' thermal preferences can be determined. Furthermore, a bio-signal from people, which can be used as an indicator for thermal sensation, should be identify. Our study only examined the thermal response of people while they were lying on their back and did not account for different body positions. This factor may have an impact on the amount of heat transfer from the body to the environment. This needs to be studied. How to identify the comfort needs of occupants and how to control them in time are the research directions for the development of the VM intelligent control systems in the future.

5. Conclusion

The present study used real-time control of the BTME by the VM combined with local heating device installed on the feet and the response of 30 subjects to the BTME was examined. The following conclusions were drawn:

1) At 19°C and 23°C, uncomfortable local cooling was reported and therefore, local heating was needed.

2) Local thermal sensation at feet improved for most of the subjects. For some of the subjects, the applied local heating was not so sufficient.

3) At 28°C, the ventilated mattress provided beneficial cooling although it required substantial increase of the ventilation flow through the mattress for the majority of the subjects.

4) The need for local heating was reported with some delay (20 - 40 min) after exposure to the bed micro environment.

6. Acknowledgement

This research was supported by the Bjarne Saxhof's Foundation for Support of Danish Research, project No 26946.

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