# Experimental Study of Thermal Environment in a Room with Mixing Ventilation

Dong-Mei Pan, Liang XIA and Ming-Yin Chan

***Abstract*—**This paper reports an experimental study on a sleeping thermal manikin in a room equipped with a mixing ventilation system. In the experimental work, heat loss from the sleeping thermal manikin was measured under different conditions. The supply air temperature was in a range of 17°C to 27°C. Apart from the heat loss of the sleeping thermal manikin, the velocity distributions and temperature distributions were also measured in the experiments for subsequent analysis.

***Keywords*—**Sleeping Environment, Mixing Ventilation System



## I. INTRODUCTION

THE current practices in air conditioning are mainly involving the situations in workplaces or other leisure places, such as shopping malls and restaurants, etc. These may however not be directly applicable to air conditioning provided for sleeping environments. However, in both tropic and sub-tropic regions, the use of air conditioning is to maintain comfortable indoor thermal environments not only in workplaces during daytime, but also in bedrooms of residences, guestrooms in hotels and wards in hospitals, at night time. Therefore, it becomes necessary to study the thermal environment in an air conditioned sleeping space in order to provide people with a thermally comfortable sleeping environment at low energy consumption.

A human being spends approximately one-third of his / her life in sleep. Sleep is not simply a state of rest, but has its own specific and positive functions [1]. Sleep can help people overcome tiredness, and is very important to one's health. In decades, numerous medical researchers have made investigations on various factors related to sleep quality [2-6]. The quality of sleep was mainly determined by two factors: mental-physical factors and bedroom environments. Although the bedroom environments consisted of many factors, including light, noise and thermal environment, the influence of thermal parameters in a sleeping environment on the quality of sleep was gradually acknowledged and documented [7-10]. The last few decades there were a few investigations studying the relationship between sleeping thermal environment and the quality of sleep.

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Miyazawa [11] suggested that the range of a thermal neutral temperature was about 22 ± 3°C. Miyazawa further showed that the room air temperature ranged between 11°C and 29°C, the quality of sleep was not significantly affected. Haskell *et al*. [8] reported that there were considerable variations of individual's sensitivity to room air temperature during sleep. It was found that the sleeping patterns of two subjects were similar when the room air temperature was maintained at 29°C. However, these investigations focused solely on the influences of room air temperature. Other factors such as air velocity, air turbulence intensity, radiant temperature of internal walls and the total insulation value of a bedding system could also considerably impact on the quality of sleep, but the acceptable range is bigger. Therefore, it is necessary to embark on studying the effects of other factors both experimentally and computationally rather than solely relying on room air temperature. For experimental studies, thermal manikins were originally introduced at least half a century ago to measure the thermal resistance of clothing. In 1977, Mihira *et al*. [12] developed a thermal manikin not only for clothing insulation measurement, but also for the evaluation of thermal environments. Although an experimental study using a thermal manikin was able to provide detailed information such as air velocity and turbulence intensity, air and wall temperatures, etc., it could be rather costly and time-consuming. Hence, a growing number of Computational Thermal Manikins (CTMs) have been proposed for the purpose of identifying and evaluating parameters that were either very expensive or very difficult to be experimentally obtained.

A CTM was firstly defined and proposed by Murakami *et al*. [13]. In the study, five CTMs were placed in five different rooms, which were air conditioned with five different air distribution systems. The air flow fields around each CTM and the convective heat transfer between each CTM and its surroundings were numerically investigated and compared. Using the same CTM, the convective and radiant heat transfer, and the moisture transfer between a CTM and its surroundings in a room with a displacement ventilation system was numerically investigated by Murakami *et al*. [14]. The study consisted of two parts: in the first part, a two-node thermoregulation model was employed to simulate the thermoregulatory process and calculate the internal heat transfer inside the CTM; in the second part, the heat and mass transfer between the CTM and its surroundings was numerically modelled. The outputs from the first part, such as sensible heat loss from occupants' skin, $Q_t$, sweating rate from occupants' skin, $m_{sk}$, etc., were used as boundary conditions for for the second part. However, the outputs from the second part, such as mean skin temperature, $t_{sk}$, mean indoor air temperature, $t_a$, water vapor partial pressure, $P_a$, etc., were used as the inputs to the first part. In addition, with the advancement of technology, a CTM with real geometry of a seated female was obtained by scanning through a thermal manikin using laser scanning technique [15]. The CTM was used in a numerical study to assess the effectiveness of a personalized ventilation (PV) system and the related thermal comfort issues. It can be seen that in previous related studies, the main concerns were on the situations where people were awake or where they were in either standing or seated posture. Concerning sleeping environments, the posture for a sleeping person was different from a standing or seated person. The metabolic rate for a sleeping person was 40 W/m$^2$ which is lower than a standing or seated person, such that the mean skin temperature of a sleeping person in the state of thermal neutrality would be higher. Thirdly, the effects of thermal insulation of clothing were mostly neglected in previous related numerical studies [13-15]. The fact was, however, in a sleeping thermal environment, the total insulation value of a bedding system would play an important role in the thermal neutrality for a sleeping person [16]. This paper reported results of the experimental study on a sleeping thermal manikin in a room with mixing ventilation. In the experimental study, the heat loss from the sleeping thermal manikin was measured under different conditions. The supply air temperature was in a range of 17 °C to 27 °C. Apart from the heat loss of the sleeping thermal manikin, the velocity distributions and temperature distributions were also measured in the experiments for subsequent analysis.

## II. Experimental Method

The experiments were conducted at The Hong Kong Polytechnic University in a thermally controlled chamber (Figure 1), and its physical size was 3600 (L) mm × 2500 (D) mm × 2500 (H) mm. The thermal manikin was placed with a supine position on a single bed with dimensions of 1900 (L) × 920 (W) mm in the chamber and the bed with mattress was located at the middle of the chamber. The supply grille was located at the center-bottom on one side wall, and the return grille was located at the center-top on the same side wall. The supply air temperature and flow rate were regulated by a DX conditioning system.

Fig. 1 Environmental Chamber

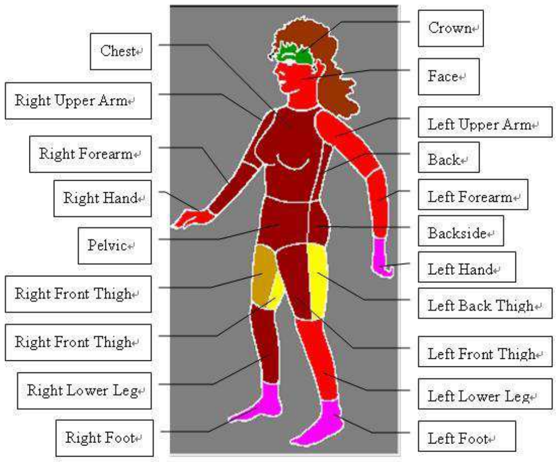


Fig. 2 Thermal Manikin

The Thermal Manikin shown in Figure 2, Alex, was divided into 20 independent segments (Left/Right: foot, low leg, front thigh, back thigh, hand, forearm, upper arm, and pelvis, backside, face, crown, chest and back), each with its own temperature sensors, and heating and computer control system to approximately simulate the skin temperature distribution of a human being. In order to correctly simulate the thermal receptors all over the body of a human body, temperature sensing elements were distributed all over the manikin surface. The manikin was heated by the same wiring used for measurement. An individual proportional integrate (PI) controller was used to produce the required mean skin temperature in each body segment of the manikin. The mean skin surface temperature, $t_{sk}$, was an important factor influencing human's thermal sensation. The following linear regression equation, which was proposed as a condition for optimal thermal comfort by Fanger [17], indicated the value of $t_{sk}$, in which the thermal neutrality may be achieved:

$$t_{sk} = 35.7 - 0.0275(M - W) \tag{1}$$

In the state of thermal neutrality for a sleeping person whose activity level was lower than a seated person:

$$M = 40 \tag{2}$$

$$W = 0 \tag{3}$$

The mean skin temperature would increase to:

$$t_{sk} = 34.6 \tag{4}$$

The skin temperature was 34.6 °C for all body segments.

Detailed air velocity and temperature measurements were accomplished by using eight lightweight sensor rigs that allowed a vertical array of sensors at desired measurement heights. At eight locations (as shown in Figure 3) in the chamber, air velocity and temperature were measured at four heights: 0.1m, 0.6m, 1.1m and 1.7m. The 0.1m, 0.6m and 1.1m levels correspond to recommended measurement heights for seated subjects as specified by AHSRAE [18]. Temperatures were measured with K-type thermocouples and velocities measured with omnidirectional anemometers having a range of 0–2.5m/s. All sensors were calibrated prior to testing. The measurement accuracy of the anemometer was ±1 % of the full scale reading. In addition, all temperature and velocity data were recorded by two Agilents 34970A automatic data logging system. During the tests, power input and mean skin temperature of each segment of the thermal manikin, supply air temperature were continuously monitored and recorded at an interval of one minute. The mean value of each parameter was calculated based on at least thirty steady-state data.

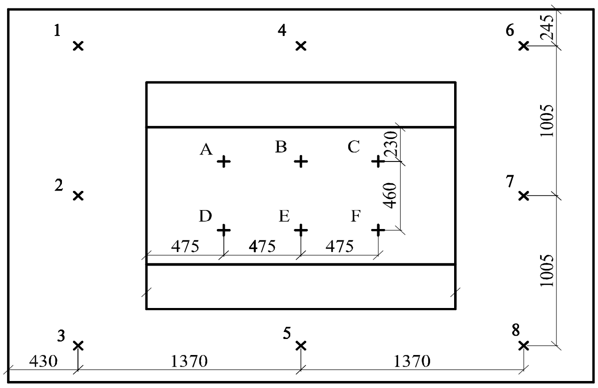

Fig. 3 Locations of air temperature and velocity measurement inside the experimental bedroom

The components of the bedding system included bedding, bed and mattress used by occupants during sleep. Two types of summer quilt (Q1 and Q2), and a blanket (B) were used in the study (as shown in Figure 4). Although a variety of mattress was available, conventional mattress could provide local insulation and better sensation. For practical reasons, it was assumed that there was no steady heat loss through the body surface where it was in contact with the mattress. However, the firmness of a mattress might affect the amount of body surface area in contact with the mattress, but the resultant variation in insulation was minimal among conventional mattresses [19]. The conventional mattress used in the study was shown in Figure 5.

Fig. 4 Blanket (B), Summer Quilt 2 (Q2), Summer Quilt 1 (Q2)


Fig. 5 A conventional mattress

## III. Experimental Results

The experiments were firstly conducted with a naked thermal manikin under various environmental conditions. The thermal manikin was covered sequentially by Q1, Q2 and B, respectively. People seldom cover their bodies with beddings entirely (at least their heads are exposed). People can change their personal insulation by covering and uncovering parts of their bodies with bedding to achieve desired thermal comfort level. To systematically study the effects, McCullough *et al.* [19] developed seventeen different configurations of body surface coverage by bedding and bed. It included total coverage (100%) to no coverage (23.3% or nude on bed). Three commonly-used configurations were selected for the experiments reported in this paper. Figure 6 shows the examples of experimental conditions and illustrates the placement of bedding on the thermal manikin, with the percentage coverage ($A_C$) of body surface area by bedding and bed indicated for each configuration [19].

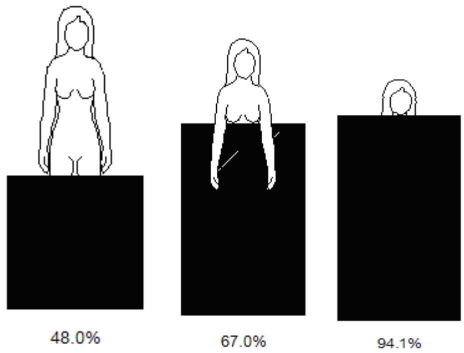

Fig. 6 Examples of experimental conditions [19]

Figure 7 shows the average air temperatures at four heights under different supply air temperatures. It can be seen that the average air temperature decreased with increasing in height since the supply grille was located on the top of the one-side wall. The temperature differences were large with low supply air temperatures. However, the temperature differences were not significant among four heights under these conditions. Hence, this mixing ventilation system could provide a uniform environment for a sleeping thermal manikin.

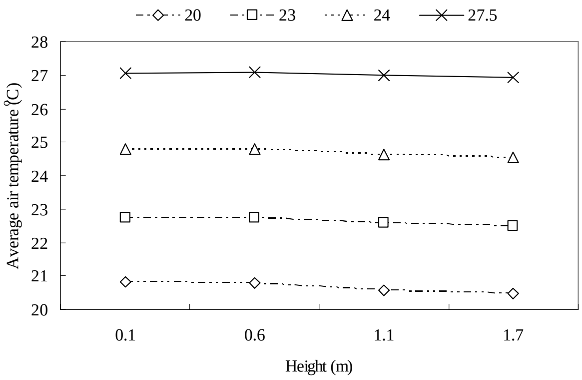


Fig. 7 Average air temperatures at four heights under different supply air temperatures

Figure 8 shows the air velocities at all points under supply air velocity 2 m/s. It can be seen that the air velocities were in a range of 0 m/s to 0.4 m/s. The air velocities were lower than 0.25 m/s at a height of 0.6 m, where it was close to the height of the bed with mattress. However, there were a few points where the air velocities were high, for example, point Location 2/ 1.7m. This point was near to the supply air grille (Fig. 3).

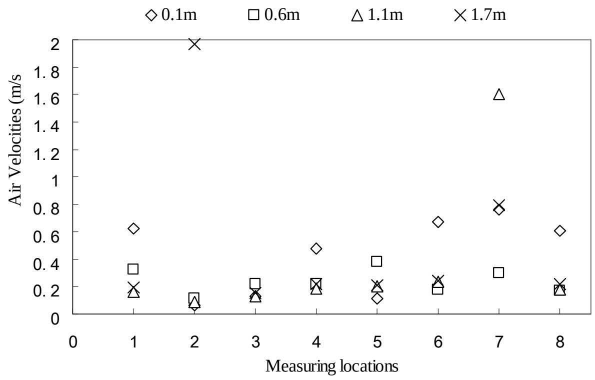


Fig. 8 Air velocities in all measurement points under supply air velocity 2 m/s

The heat loss from a naked sleeping thermal manikin may be influenced by various environmental factors, such as air temperatures, wall temperatures, air velocity and etc. Figure 9 shows the heat loss from a naked sleeping thermal manikin under various environmental conditions. The supply air temperature would significantly affect the magnitude of heat loss. The higher the supply air temperature was, the less the heat loss to the ambient was. The increase in supply air velocity from 1m/s to 1.5m/s resulted in the increase of heat loss, 7.3 W/m$^2$. It was nearly twice of 3.6 W/m$^2$, which was led by the increase in supply air velocity from 1.5 m/s to 2m/s.

The supply air flow would also affect the heat loss. The higher the supply air rate was, the higher the heat loss was. Three supply air flow rates were tested. The increase in supply air temperature of 1 K would result in an increase of heat loss 5.27 W/m$^2$, 5.4 W/m$^2$ and 5.57 W/m$^2$, successively.

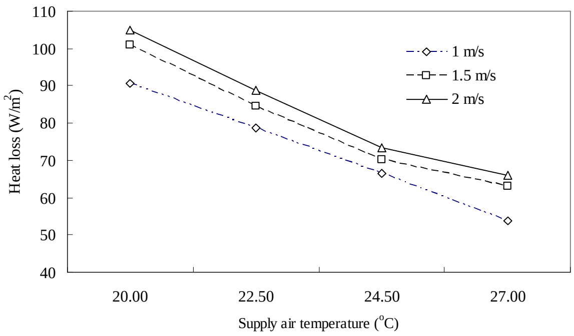


Fig. 9 Entire body heat loss from a naked sleeping thermal manikin under various environmental conditions

Besides environmental factors, the total insulation value of a bedding system plays an important role in the heat loss from a covered sleeping thermal manikin [16] to ambient. The thermal resistance of a bedding, $r_b$, and percentage coverage of body surface area by bedding and bed, $A_C$ are crucial in determining heat exchange during sleeping condition [19, 20-21]. The supply air flow rate and corresponding temperature were fixed at 2m/s and 22 °C, respectively in the experiments in order to investigate the effects of the heat loss from a covered sleeping thermal manikin. Figure 10 shows the heat loss from a covered sleeping thermal manikin with three different beddings at three different *Ac*. It can be seen that *Ac* would significantly affect the heat loss from a covered thermal manikin. The higher the *Ac* was, the less the heat loss from a covered thermal manikin was. Types of bedding would significantly affect the heat loss from a covered sleeping thermal manikin. The difference in heat loss resulted from the bedding became large when *Ac* was large.

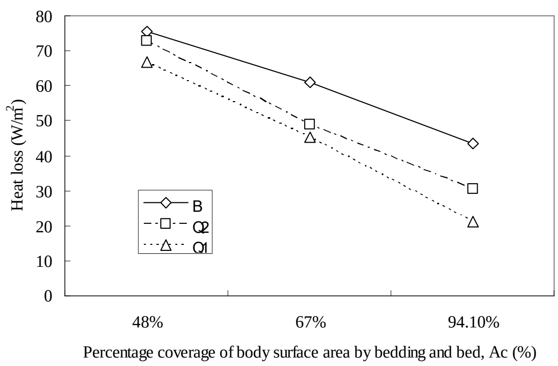


Fig. 10 shows the heat loss from a covered sleeping thermal manikin with three different beddings at three different *Ac*

## IV. Conclusions

In this study, the heat loss from a sleeping thermal manikin was measured under different conditions with an exception from a sleeping thermal manikin. The velocity distributions and temperature distributions were also measured in the experiments. The results suggested that the supply air temperature and air flow rate affected significantly the heat loss from sleeping objects to ambient. The total insulation value of a bedding system played an important part in the process of heat loss from a covered sleeping thermal manikin to the space.

## ACKNOWLEDGMENT

The authors acknowledge the funding supports A-SA10 and A-PL09 from The Hong Kong Polytechnic University.

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