Purdue University
Purdue e-Pubs

International High Performance Buildings Conference

School of Mechanical Engineering

July 2018

A Numerical Study On The Indoor Thermal Environment Served By A Novel Air Source Heat Pump Powered Bed-Based Space Heating (ASHP-BBSH) System

Guanyu Fang
The Hong Kong Polytechnic University, Department of Building Services Engineering, Hong Kong S.A.R. (China), 16902942r@connect.polyu.hk

Jing Du
The Hong Kong Polytechnic University, Department of Building Services Engineering, Hong Kong S.A.R. (China), dujing.toni@gmail.com

Ming-yin Chan
The Hong Kong Polytechnic University, Department of Building Services Engineering, Hong Kong S.A.R. (China), ming-yin.chan@polyu.edu.hk

Shiming Deng
The Hong Kong Polytechnic University, Department of Building Services Engineering, Hong Kong S.A.R. (China), besmd@polyu.edu.hk

A numerical study on the indoor thermal environment served by a novel air source heat pump powered bed-based space heating (ASHP-BBSH) system

Guanyu Fang, Jing Du, Ming-yin Chan, Shi Ming DENG*

[1]The Hong Kong Polytechnic University, Department of Building Services Engineering,
Hong Kong SAR, China
Tel: 852-27665859, Fax: 852-27657198, Email: besmd@polyu.edu.hk

* Corresponding Author

ABSTRACT

A numerical study on the indoor thermal environment served a novel air source heat pump powered bed-based space radiation heating (ASHP-BBSH) system is reported in this paper. This novel system combines the merits from a Chinese Kang, or a heated bed, widely used in northern rural China and a standard ASHP system, which can provide localized space heating via both convection and radiation to maintain a comfortable indoor thermal environment, at reduced energy use. In this novel bed-based system, a bed is heated and thus used as a radiator for providing space heating at both daytime and nighttime. In this paper, firstly, a numerical model for a bedroom with a heated bed was firstly built and a manikin with simplified dimensions and physiological shape sitting on the heated bed has been added to the numerical model. Secondly, using the model, the relationships between indoor thermal environment and a number of influencing factors, including the bed surface temperature, heating area were numerically studied. Thirdly, a comparison between the novel system and a standard ASHP system was numerically conducted to demonstrate the advantages of the novel bed-based space heating system. The numerical results show that compared with a standard ASHP system, a better thermal comfort level and higher energy saving potential can be achieved by applying the ASHP-BBSH system. Necessary parameters for the system design and operation in the follow-up experimental work were provided.

Key words: ASHP; radiant heating; thermal comfort; CFD; simplified manikin

1. INTRODUCTION

The purpose of using heating in a room is to provide adequate thermal comfort level serving occupants inside especially in winter. However, heating could consume a lot of energy, as much as 17GJ per household per year in China (Zhang, 2004) and cause serious air pollution and environmental damage (Ando et al., 1998) . Therefore, it is of highly demand to develop novel heating systems, to reduce energy consumption while maintaining a suitable level of indoor thermal comfort.

There are about 85% of rural homes in northern China use Kang for localized heating in their bedroom, which can be regarded as an bed based radiant heating system (Li et al., 2009). Chinese Kang Radiation heating systems have been widely adopted nowadays since it can achieve a high thermal comfort level, quiet operation, energy saving potential, integration with building design, and so on. During the past decades, to achieve better environmental protection and energy saving potential, different types of novel Chinese Kang systems have been developed, such as solar Chinese Kang system (Zhao et al., 2017), Chinese Kang with forced convection system (Wang et al., 2014). Compared to a conventional ASHP system which depends on convection only, a Chinese Kang system provides heating by the combination of radiation and convection.

Besides the Kang system, an air source heat pump (ASHP) is one of the most common system for heating not only in China but also in many other countries. ASHP is a reliable system with low initial cost, simple maintenance and easy operation (Dong et al., 2018). During the cold seasons, ASHP extracts thermal energy from ambient air and heat the indoor conditioned space by the delivered energy. Currently, most of the conventional ASHP systems adopt finned tube heat exchanger with a fan coupled as heating terminals indoor, occupants may suffer from strong draught sensation and dry eye problem.

Since the Air source heat pumps (ASHPs) are environmentally friendly and reliable systems and are relatively easy and inexpensive to install, it is necessary to combine the merits of a conventional ASHP system and a Chinese Kang system to produce a novel air source heat pump powered bed-based space radiation heating (ASHP-BBSH) system.

2. NUMERICAL STUDY ON THE INDOOR THERMAL ENVIRONMENT SERVED BY A NOVEL AIR SOURCE HEAT PUMP POWERED BED-BASED SPACE HEATING (ASHP-BBSH) SYSTEM

2.1. Methodology

The geometry model of the bedroom was firstly built. The size of the bedroom (W×D×H) was 2600 mm × 3700 mm × 3290 mm. On its external wall, there was an external window (1500 mm × 1000 mm). In this bedroom, a full-size heated bed (2000 mm × 1500mm × 900 mm) was placed inside to supply heating radiatively and conductively, and there was an occupied zone with a thermal manikin sitting above the bed with a dimension of 2000 mm × 1500 mm ×1000mm. An ASHP indoor unit was placed at 2500 mm above the floor level on the wall adjacent to the manikin. The simulation bedroom layout is shown in Figure 1. The boundary conditions for the CFD method including emissivity and thermal conditions are summarized in Table 1.

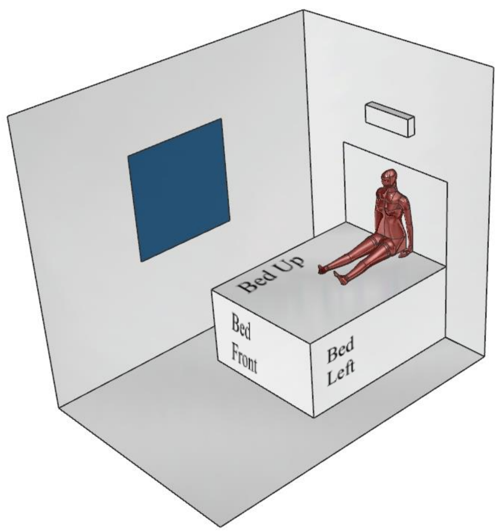

Figure 1: The simulation bedroom layout under the ASHP-BBSH system

Table 1: Boundary conditions of the simulation bedroom

Boundary	External wall	External window	Floor	Other walls	Bed	Thermal manikin
Emissivity	0.9	0.94	0.3	0.07	0.9	0.98
Thermal conditions	Fixed temperature: 4 ºC	Fixed temperature: 4 ºC	Adiabatic	Adiabatic	Adiabatic	Fixed skin temperature: 36.4 ºC

ICEM CFD was selected to generate grids (*ANSYS ICEM CFD Help Manual*, 2010) for the occupied zone and unoccupied zone separately. Due to the complex geometry of thermal manikin, for the occupied zone, unstructured grids were generated and prism mesh was used for the entire wall representing the manikin surface (Mao, 2015). For the unoccupied zone, structured grids were generated to reduce the number of total grids. Fluent was selected to

simulate and calculate the working conditions of the novel system. The SST turbulence model was selected to calculate turbulent flow parameters, because it was proven that the model can show the flow features satisfactorily, and predict accurately air velocity and temperature distributions inside a room (Ning et al., 2014; Stamou & Katsiris, 2006). Also, the Discrete Ordinates model (DO) was used to compute the radiation exchange in the simulation bedroom.
In this study, first of all, three different bed surface temperatures and two different bed heating area were studied: 30 ºC, 35 ºC and 40 ºC, respectively; up bed surface only (2000mm × 1500mm) and the combination front, left and right bed surfaces (1500mm × 900mm + 2 × 2000mm × 900mm) , as shown in Figure 2, and marked as Bed Up and Bed FLR. Then in the following section, the coming section presented a comparison study between the bed radiation heating terminals and conventional convective terminal.

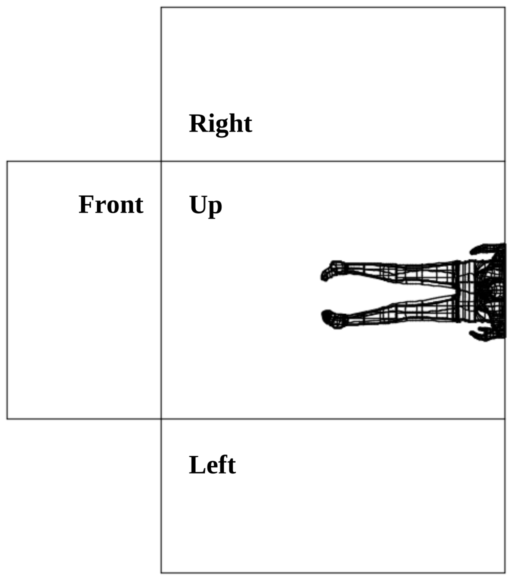

Figure 2: Plan view of the heating bed

2.2. Relationships between indoor thermal environment and influencing factors for bed-based radiant heating system

The volume averaged air temperatures and air velocity magnitude are measured as indoor environment indicators both in the occupied and the unoccupied zones, at different surface temperatures of bed-based radiant heating system as shown in Figure 3. It can be seen that, with an increasing temperature in the bed-based radiant heating system, air temperature would be increased both inside the occupied zone and the unoccupied zone. However, the both the air temperature and increasing ratio of the FLR heating system is much higher than that of the Up heating system. The air temperature differences between the two systems is about 5 ºC. This is mainly because that the total heating area of the FLR heating system (4.95 m^2) is 65% larger than that of the Up heating system (3 m^2). Besides that, since the thermal manikin is lying on the Up surface of the bed, there would be less heating area exposed to the bedroom indoor environment directly. Moreover, the temperature differences between the occupied zone and the unoccupied zone are ranging from 0.6 ºC to 1 ºC, showing that the bed-based radiant heating system could achieve a energy-saving potential. For the volume averaged air velocity, there were no significant change when increasing the temperature of the bed-based heating system. It can be seen that the volume averaged air velocities for the FLR heating system are higher than the Up heating system with the same bed surface temperature, ranging from 0.01 to 0.04 m/s.
In this section, volume averaged operative temperature inside the occupied zone was measured as an parameter to describe the thermal environment generated by the bed-based radiant heating system. The operative temperature is a comprehensive index that integrates convective and radiative heat transfer, and thus reflects the thermal environment in the experimental bedroom, as expressed in Equation (1).

$$t_o = \frac{h_r \overline{t}_r + h_c t_a}{h_r + h_c} \tag{1}$$

Where $\overline{t_r}$ and t_a are mean radiant temperature and air temperature, respectively; h_r is radiative heat transfer coefficient, W/m^2·K, which was determined at 4.7 W/m^2·K for most calculations; h_c is convective heat transfer coefficient, W/m^2·K, which was assumed be 5.1 W/m^2·K when the air velocity is lower than 0.15 m/s.

Figure 4 showed the simulated volume averaged operative temperature with different bed surface temperature under FLR heating and Up heating, respectively. It can be seen that, with an increase in the bed surface temperature from 30 °C to 40 °C, there was an obvious rise in operative temperature, from 15.1 to 19 °C and 17.7 to 22.7 °C for Up and FLR heating, respectively. The operative temperature raise about 2 °C and 2.5 °C for Up and FLR heating when increase the surface temperature of 5 °C. At the same time, the operative temperature are about 3 °C higher for the FLR heating system than that of the Up heating system with the same surface temperature. No obvious relationship between the volume averaged operative temperature and the velocity was found.

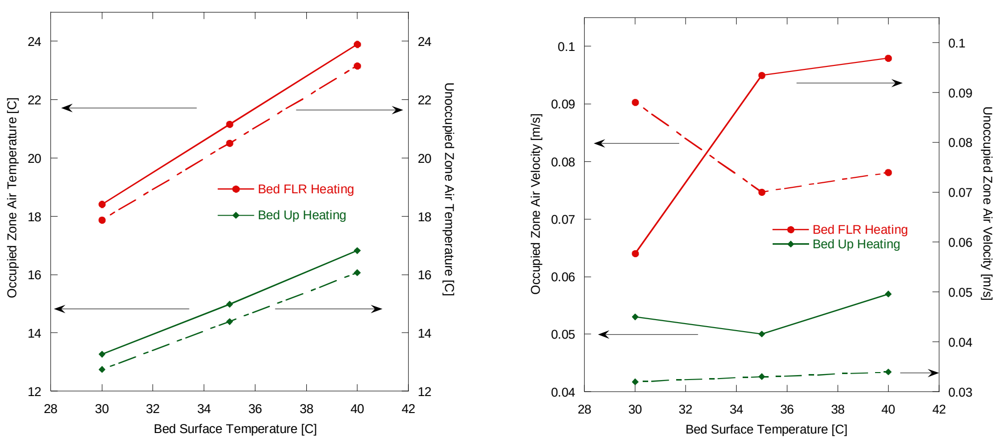

Figure 3. The relationship between the bed surface temperature and (a) volume-averaged air temperature (b) volume-averaged velocity inside the occupied and unoccupied zone.

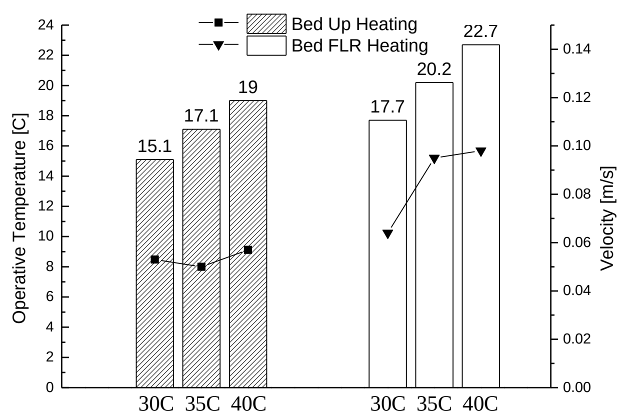

Figure 4. The volume-averaged operative temperatures and volume-averaged velocities inside the occupied zone.

2.3. A comparison study of the indoor thermal environment between the bed-based radiant heating system and conventional convective heating system

The simulated conventional convective terminal is set with boundary conditions that with an air temperature of 30 °C and velocity magnitude of 1.6m/s at the velocity outlet. On the contrast, two cases under bed-based radiant heating with bed surface temperature of 40 °C were marked as Bed FLR 40C and Bed Up 40C respectively, and the case with convective heating terminal was marked as AC. In order to compare the thermal environment inside the occupied zone under two heating system, the temperature and velocity distributions near the manikin at line 1 were measured, as showed in Figure 6. Line 1 is of 1m long with the start point is on the bed surface, and is parallel to the Z direction and is located at 0.5 m to the central of the manikin head at X direction and 0.5 m to the wall adjacent to the manikin at Y direction, as showed in Figure 5.

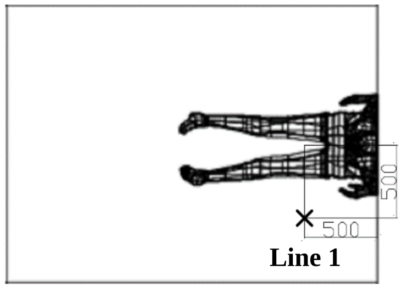

Figure 5: The location of Line 1.

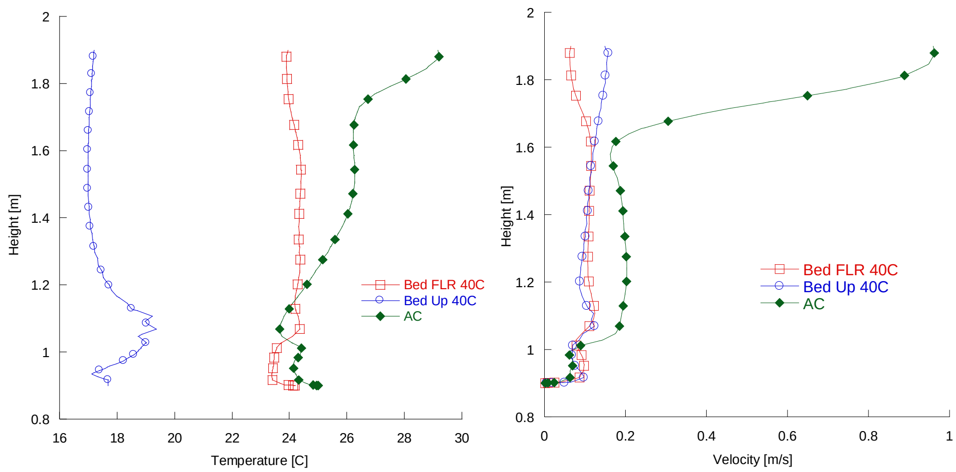

Figure 6: The comparisons of airflow and temperature distributions near the manikin.

It can be seen that the air velocity is low at the at the height of 0.9 m to 1m for all three cases. However, the velocity magnitude of the case with convective heating terminal increased to about 0.2 m/s when the height is over than 1m, and even increased sharply when the height is above 1.6m. For the two bed-based radiant heating cases, the velocity magnitude stayed around 0.15 m/s throughout Line 1. It can be found the air temperature is relatively stable at the initial part from beginning to 1.1 m for the case Bed FLR 40C and AC at around 24 ºC. Since the bed up surface is heated at the case of Bed Up 40C meanwhile the manikin is set at 36.4 ºC, the coupling effect led to a higher air temperature fluctuation compared to the two bed based radiant heating cases. The air temperature of AC heating changed expeditiously when the height is above 1.1m. The air velocity, temperature and gradient can be easily calculated as listed in Table 2.

Table 2: Boundary conditions of the simulation bedroom

Thermal environment parameters	Temperature gradient (ºC/m)	Highest velocity (m/s)
Bed FLR 40C	1	0.12
Bed Up 40C	2	0.15
AC	4.1	0.96

The air velocity and temperature distribution indicates that the bed-based radiant heating system can generate a uniform thermal environment while the convective based system could not. The non-uniformity of the thermal environment would cause an uncomfortable sense of warm air blowing.
The volume averaged operative temperatures of the three cases were measured, as seen in Figure 7. The operative temperature of the cases Bed Up, Bed FLR and AC were 19 ºC, 22.7 ºC and 23.7 ºC, respectively. Therefore, the thermal environment of bed-based up surface radiant heating may cause a sense of cold while the other two cases can provide a warmer environment.

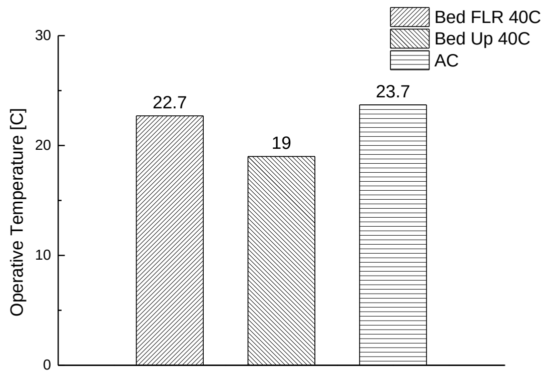

Figure 7: The comparisons of volume-averaged operative temperatures inside the occupied zone with different heating methods.

3. CONCLUSION

In this paper, a novel air source heat pump bed based radiant heating system was introduced. The design parameters of bed surface temperature and bed heating surface area of the ASHP-BBSH system were numerically studied. The results showed that the system with bed front, left and right surfaces heating could get a warmer thermal environment the system with up surface heating under same bed surface temperature. Then a comparative study showed that the ASHP-BBSH system can solve the limits of traditional convective based heating system: (1) Temperature gradient (2) The sense of warm air blowing. Furthermore, the results give a clear guidance to the experiment design in the future work.

REFERENCES

Ando, M., Tadano, M., Asanuma, S., Tamura, K., Matsushima, S., Watanabe, T., . . . Liang, C. (1998). Health effects of indoor fluoride pollution from coal burning in China. Environmental Health Perspectives, 106(5), 239.
ANSYS ICEM CFD Help Manual. (2010). ANSYS, Inc.
Dong, J., Zhang, L., Deng, S., Yang, B., & Huang, S. (2018). An experimental study on a novel radiant-convective heating system based on air source heat pump. Energy and Buildings, 158(Supplement C), 812-821. doi:https://doi.org/10.1016/j.enbuild.2017.10.065
Li, Y., Zhuang, Z., & Liu, J. (2009). Chinese kangs and building energy consumption. Science Bulletin, 54(6), 992-1002. doi:10.1007/s11434-009-0129-z
Mao, N. (2015). A study on thermal environmental control, indoor air quality and energy efficiency using task\ambient air conditioning (TAC) systems in sleeping environments in the subtropics. The Hong Kong Polytechnic University.
Ning, M., Dongmei, P., Mingyin, C., & Shiming, D. (2014). Experimental and numerical studies on the performance evaluation of a bed-based task/ambient air conditioning (TAC) system. Applied Energy, 136, 956-967.
Stamou, A., & Katsiris, I. (2006). Verification of a CFD model for indoor airflow and heat transfer. Building and Environment, 41(9), 1171-1181. doi:http://dx.doi.org/10.1016/j.buildenv.2005.06.029
Wang, P., Shan, M., Xiong, D., & Yang, X. (2014). A new Chinese Kang with forced convection: System design and thermal performance measurements. Energy and Buildings, 85, 410-415. doi:10.1016/j.enbuild.2014.09.073
Zhang, Q. (2004). Residential energy consumption in China and its comparison with Japan, Canada, and USA. Energy and Buildings, 36(12), 1217-1225. doi:https://doi.org/10.1016/j.enbuild.2003.08.002

Zhao, D., Ji, J., Yu, H., Wei, W., & Zheng, H. (2017). Numerical and experimental study of a combined solar Chinese kang and solar air heating system based on Qinghai demonstration building. Energy and Buildings, 143, 61-70. doi:10.1016/j.enbuild.2017.03.023

ACKNOWLEDGEMENT

The authors are grateful to the funding support for the Hong Kong Polytechnic University.