International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 0714

COMPARISON OF THE SLEEPING THERMAL ENVIRONMENT BETWEEN CONVECTION-BASED SYSTEM AND BED-BASED HEATING SYSTEM POWERED BY AIR SOURCE HEAT PUMP TECHNOLOGY IN WINTER

Qingxin Chen[1], Guanyu Fang [1], Shiming Deng[1]

1 Department of Building Services Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong SAR, China

ABSTRACT

Air Source Heat Pump (ASHP) system serves as a highly reliable system with long lifespan might be an available heat source for traditional Chinese Kang, which would solve the problem of waste pollution from a traditional Chinese fire Kang as well as keep the original advantages of Chinese Kang, such as localized heating and uniform airflow distribution. Based on this assumption, a novel system called bed-based heating system powered by ASHP was proposed.

To prove the feasibility of the novel system and find out the difference of thermal performance to conventional heating system, this paper set up computational fluid dynamics (CFD) models for the novel system to find out the suitable covering bedding materials settings, then make comparison with traditional convection-based system. According to simulated results, the novel system have better thermal performance than convection-based system, such as moderate airflow(less than 0.1m/s) and good thermal comfort(ADPI:80%), but the case with 5mm cotton mattress and 15mm quilt may be not be suitable for the novel system to provide satisfied thermal comfort. Therefore, finding suitable covering bedding materials to improve the comfort and optimize the novel system would be the further work.

Keywords: Air Source Heat Pump, bed-based system, convection-based system, thermal comfort, CFD

NONMENCLATURE

ASHP	Air Source Heat Pump	M	Mattress thickness(mm)
CFD	Computational Fluid Dynamics	Q	Quilt thickness(mm)
AVE T	Average temperature(℃)		
AVE V	Average velocity(m/s)	OZ	Occupied zone
ADPI	Air Diffusion Performance Index	UZ	Unoccupied zone
ΔET	effective draft temperature, (℃)	u_i	air velocity at a certain point in the work area, (m/s)
t_i	the workspace of air temperature at some point, (℃)	t_n	the given indoor design temperature, (℃)

1. INTRODUCTION

Sleep is essential for improvement for physical and psychological health [1]. Thermal environment has a great impact on the quality of human sleep[1], therefore heating systems are widely adopted during sleeping in winter, such as Chinese Kang [2], split-type air conditioning system. However, these two system have some unsatisfactory aspects, such as air pollution for fuel burning from Chinese Kang [3] and drought issue for convection-based ASHP systems [4]. ASHP system as a highly reliable system with long lifespan [5] might be an available substitution of the heat source for traditional Chinese fire Kang, which would avoid waste pollution from Chinese Kang [6] as well as keep the original advantages of localized heating and uniform airflow distribution [3]. Based on these concepts, a novel system called bed-based system powered by ASHP was proposed.This paper will prove the feasibility of a novel bed-based heating system and discuss the difference of thermal performance between the novel system and convection-based systemsboth powered by ASHP technology, then follow by optimization of the novel system for a better comfortable sleeping thermal environment.

2. METHODOLOGY

2.1 Introduction

Firstly, to build up the models of a bed-based system and a convection-based system respectively for numerical simulation by using CFD. Secondly, the models will be validated by using previous experimental

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).

data. Finally, cases simulation are studied using the validated model and conclusions are given.

2.2 Modelling

2.3.1 Grid generation for modelling

Generating grids plays a key role in CFD modelling for computational stability and results accuracy. In this study, the simulation space is divided into two parts： The occupied zone is at the designated space of 0.6 m high on top of the heated bed, and the rest of the indoor space is the unoccupied zone [1]. The sectional views of the mesh for the computational domain including both the occupied and the unoccupied zones at the two settings are shown in Fig.1. The height of the first layer for prism mesh from the surface of thermal manikin was set at 0.4 mm, and 10 layers of prism mesh were generated in wall-normal direction to guarantee y+<1 and to provide a better computational result [7]. In the unoccupied zone, structured grids were generated so as to save computational time , [8]. The total number of cells generated was 2,929,773.

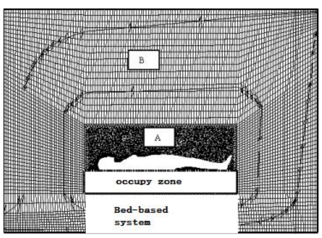


Fig.1 Diagram of mashing [1]

2.3.2 The CFD boundary conditions setting

The setting of CFD is based on the data of previous experimental work and relevant references. The skin temperature of the manikin was set at 36.4°C, to represent a state of thermal neutrality of a sleeping person[8]. The turbulence model and radiation model were SST k-ε and Discrete Ordinates (DO), respectively. According to experimental data, the emissivities of the manikin, the room external wall and external window, were set at 0.98, 0.9 and 0.94, respectively. When simulating the cases under six heat transfer walls, the parameters of all walls are the same as the external wall. The outdoor temperature was set at 7℃ based on the winter average temperature in non-central heating area [9]. The inlet supply air temperature of the convection-based terminal is 30℃ and the heated bed was sat at 43℃ according to ASHRAE Standard [10]. The related information about part of boundary conditions are shown in Table 1. According to the total insulation value of the bedding materials reported by Lin [11], the thickness of cotton mattress and quilt could be obtained.

Table 1 Boundary conditions

Boundary	Emissivity	Thermal conditions
External wall	0.9	Fixed temperature:10℃
External window	0.94	Fixed temperature:10℃
Floor	0.3	Adiabatic
Other walls	0.07	Adiabatic
Bed	0.9	Adiabatic
Thermal manikin	0.98	Fixed skin temperature: 36.4℃
Heated Bed	0.9	Fixed temperature: 43℃
Outdoor Temperature	/	Fixed temperature: 7℃
Inlet air supply	/	Fixed temperature: 30℃

2.3 Model Validation

The experimental work is expected to prove the accuracy of the CFD models by comparing the similarity of simulated and experimental data. The process of experiment would be in an environmental chamber with an experimental set-up, which could be separated into a simulated indoor space and a simulated outdoor space. The provisional layout of the experimental set-up and the schematic diagram of the proposed system are shown in Fig.2 and Fig.3 respectively.

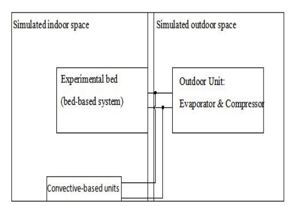


Fig.2. Complete experimental set-up

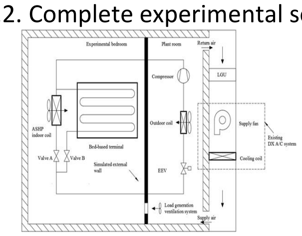


Fig.3. The schematic diagram of the novel system

There are two components in the indoor heating space: the convection-based terminal and the Kang bed, as shown in Fig.3. The Kang bed is the key part of the bed-based system powered by ASHP.

In the experiment, six lines of measuring points were made to compare with the simulated data, the positions of measurement lines in CFD models are shown as Fig.4.

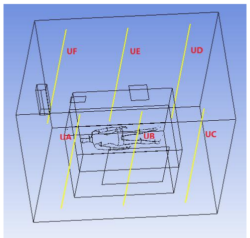


Fig.4 The positions of measurement lines

As the below Table 2 shown, the simulation results are in well corresponding with the experimental study, with the maximum difference of 0.5 ℃ (about 0.17%), suggesting that the model is validated [8].

Table 2 Validation results comparison

	Zoom Height(m)	Temperature(K) simulated data	Temperature(K) experimental data	Comparison		Temperature(K) simulated data	Temperature(K) experimental data	Comparison
UA	0.10	290.32	289.97	-0.12%	UD	290.30	289.86	-0.15%
	0.60	292.73	292.69	-0.01%		292.75	292.56	-0.07%
	1.10	294.73	294.62	-0.04%		294.79	294.67	-0.04%
	1.40	295.74	295.81	0.02%		295.80	295.94	0.05%
	1.70	295.62	295.2	-0.14%		295.63	295.17	-0.16%
UB	0.10	291.69	291.36	-0.11%	UE	291.94	292.44	0.17%
	0.60	292.74	292.8	0.02%		293.88	294.09	0.07%
	1.10	295.05	294.62	-0.15%		295.29	295.4	0.04%
	1.40	295.12	294.68	-0.15%		295.69	295.37	-0.14%
	1.70	295.96	295.83	-0.04%		295.84	295.89	0.02%
UC	0.10	291.04	290.78	-0.09%	UF	290.91	290.74	-0.06%
	0.60	292.76	292.52	-0.08%		292.93	293.32	0.13%
	1.10	294.36	294.13	-0.11%		295.02	295.45	0.15%
	1.40	295.76	295.32	-0.15%		295.68	295.28	-0.14%
	1.70	294.96	294.79	-0.06%		295.99	295.64	-0.12%

2.4 Case setting and analysis

The simulation study is divided into into 5 groups with 10 cases, and the cases and groups setting are demonstrated in below table 3 and 4. Firstly, Group A studies the impact of mattress thickness on the heating performance of thenovel bed-based system. Secondly, Group B aims to find out the influence of quilt thickness for the new system though comparison of Case 4 and Case 5. The next three groups would compare thermal performance betweenthe novel bed-based system and conventional convection-based system.

Table 3 Cases setting

No.	Heating system	Variable	Variable type	Numerical value	Other conditions
1	Bed-based system powered by ASHP	Thermal conductivity of mattress	Mattress thickness(M)	M200mm+Q89mm	One heat transfer wall
2				M28mm+Q89mm	
3				M10mm+Q89mm	
4				M5mm+Q89mm	
5		Thermal conductivity of quilt	Quilt thickness(Q)	M5mm+Q15mm	
6		Thermal conductivity of Bedding materials	(M) +(Q)	M5mm+Q15mm	Six heat transfer walls
7				M0mm+Q0mm	
8	Convection-based system powered by ASHP	Thermal conductivity of quilt	(Q)	M5mm+Q15mm	One heat transfer wall
9		Thermal conductivity of Bedding materials	(M) +(Q)	M5mm+Q15mm	Six heat transfer walls
10				M0mm+Q0mm	

Table 4 Case study group setting

No.	Variable Type	Variable	Comparison No.	Comparison objects	Other conditions
A	Mattress thickness	Thermal conductivity of mattress	1+2+3+4	Bed-based system	Only one heat transfer wall
B	Quilt thickness	Thermal conductivity of quilt	4+5	Bed-based system	
C	Heating system	/	5+8	Bed-based +Convective-based(in light blanket)	
D	Heating system	/	6+9	Bed-based +Convective-based(in light blanket)	Six heat transfer walls
E	Heating system	/	7+10	Bed-based +Convective-based(in no beddings)	

For the measuring indexes, the temperature and air velocity in the simulated space as well as ADPI is selected.

The equations of ADPI [12] is below,

$$\Delta ET = (t_i - t_n) - 7.66(u_i - 0.15) \qquad (2/1)$$

$$ADPI = \frac{\text{The number of measurement points meeted the requirements: } -1.7 < \Delta ET < +1.1}{\text{The total number of points}} \qquad (2/2)$$

The higher the value of ADPI, the higher the proportion of people who feel comfortable. In general, ADPI should be greater than 80% [12]. In cases study, the given indoor design temperature t_{n1} for bed-based system is set as 15.8 ℃ [13], while t_{n2} for convection-based system is set as 20℃ according to GB50019 [14]. The measurement points in occupied zone from UA, UB, UC, UE, UF (shown in Fig.5) are selected as the ADPI measurement points with a total number of 50.

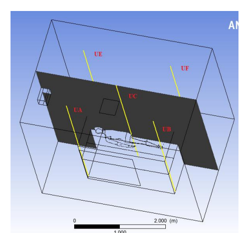


Fig.5 The schematic diagram of measuring line position

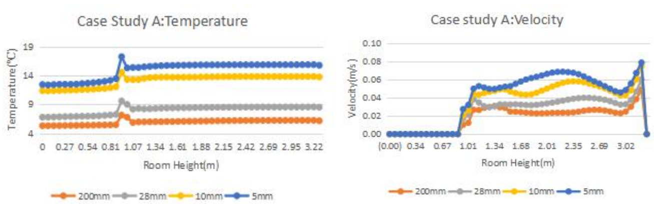
3. RESULTS AND DISCUSSION

3.1 The mattress thickness comparison (Case Study Group A)

As seen in Fig.6, it is obvious that as the thickness of mattress decreasing, the indoor temperature is rising. When the mattress thickness decreased to 5mm, the air temperature above bed stabilized at around 16 ℃， which is fairly close to the ideal temperature of 15.8℃. In addition, a view from Fig.7 can be found that as the mattress thickness decreases, the air velocity increases slightly with minor fluctuations. The maximum value is about 0.08m/s, which is still within the comfort zone for human sleeping. Therefore, 5mm mattress would be considered as the suitable thickness of the mattress under experimental conditions.

Table 5 Simulated results comparison

Case Study A	M200mm+ Q89mm	M28mm +Q89mm	M10mm +Q89mm	M5mm+ Q89mm
AVE T in OZ	5.77	8.20	13.41	15.42
AVE V in OZ	0.019	0.034	0.046	0.053



(a) Temperature comparison (b) Velocity comparison

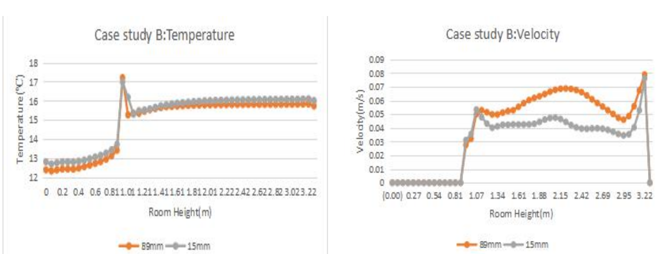
Fig.6 Comparison of temperature and velocity

3.2 Quilt thickness comparison (Case Study Group B)

The thermal performance for thenovel bed-based system with different thickness of covering as shown in Fig.8. However, the novel system with 15mm quilt could provide a temperature of 15.67 ℃ with only 0.8% difference to the referenced state(15.8 ℃) [13] and a smoother airflow (no more than 0.09m/s), providing a cozy sleeping thermal environment as shown Fig.8 and Fig.9.

Table 6 Simulated results comparison

Case Study B	AVE T in OZ	AVE V in OZ
M5mm+Q89mm	15.42	0.053
M5mm+Q15mm	15.67	0.057



(a) Temperature comparison (b) Velocity comparison

Fig.7 Comparison of temperature and velocity

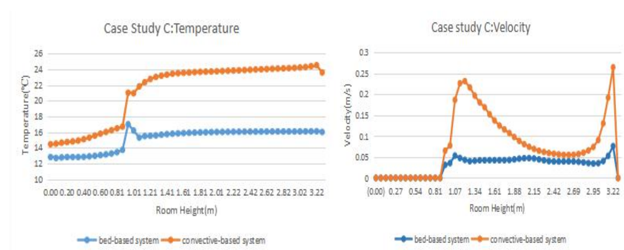
3.3 Comparison between bed-based system heated by ASHP and convection-based system

3.3.1 Two systems in light blanket (Under laboratory conditions setting) (Case Study Group C)

Under laboratory conditions, 5mm mattress and 15mm quilt seems suitable for the novel bed-based system to provide a highly comfortable sleeping thermal environment, with 96% of ADPI. Meanwhile, only 14% of ADPI for convection-based system may not be an ideal state of sleeping thermal environment. In addition, the variation of air velocity is more fluctuated for occupied zone using convection-based system compared with that in bed-based system according to Fig.10. People may suffer from head-blowing feeling under such high speed airflow. On the contrary, the air velocity (no more than 0.1m/s) is steady and slight under the new bed-based system working, which is suitable for sleep.

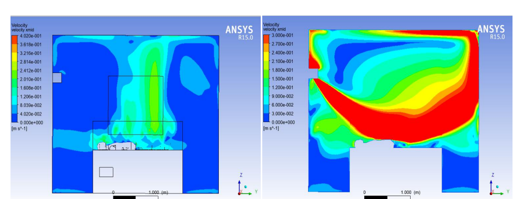
Table 7 Simulated results comparison

M5mm+Q15mm (in one heat transfer wall)	AVE T in OZ	AVE V in OZ	ADPI
Bed-based system	15.67	0.057	96%
Convection-based system	23.03	0.22	14%



(a) Temperature comparison (b) Velocity comparison

Fig.8. Comparison of temperature and velocity



(a)Bed-based system(b)Convection-based system

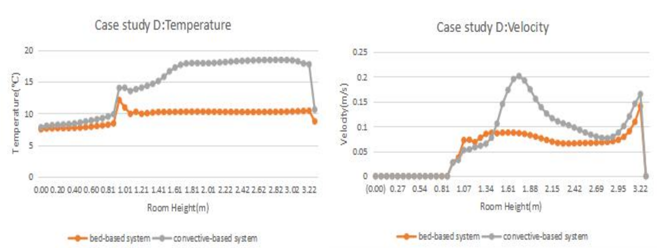
Fig.9. Velocity contour of two systems

3.3.2 Two systems in light blanket (Under six heat transfer walls) (Case Study Group D)

Although the temperature around the bed using the novel bed-based system is close to 15.8 ^{o}C, the overall thermal performance is not satisfactory. As shown in Table 5, the ADPI of bed-based system heated by ASHP system is fairly low (0%), even lower than that of convection-based system (4%). Both systems did not perform very well with six heat transfer walls as shown inFig.14 and Fig.15. However, the air flow under the new system working is low and steady compared to traditional convection-based system. Therefore, finding the suitable covering bedding materials will be the further work.

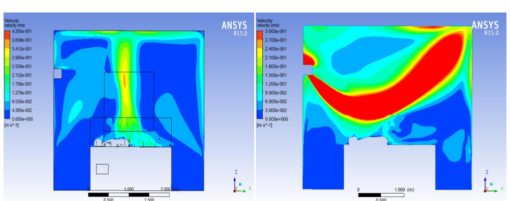
Table 8 Simulated results comparison

M5mm+Q15mm (in six heat transfer walls)	AVE T in OZ	AVE V in OZ	ADPI
Bed-based system	10.21	0.066	0%
Convection-based system	14.22	0.070	4%



(a) Temperature comparison (b) Velocity comparison

Fig.10 Comparison of temperature and velocity



(a)Bed-based system (b)Convection-based system

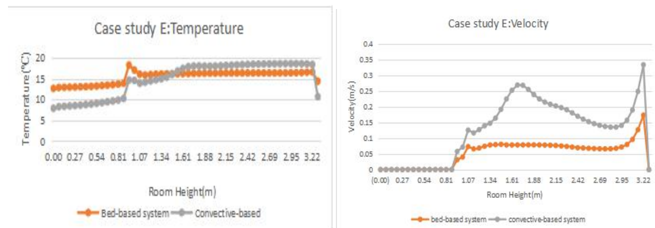
Fig.11. Velocity contours of two systems

3.3.3 Two systems without bedding materials (Under Under simulated real environment conditions setting) (Case Study Group E)

Before looking for another bedding materials that are more suitable for the novel system, it is essential to determine that the novel bed-based system can achieve the desired heating effect with six heat transfer walls. In the absence of covering bedding materials, the heating performance of convection-based system is not much different from that of the previous case study, but the heating performance of the novel system could be almost satisfactory with 80% of ADPI, as shown in Table 6. And the moderate and steady airflow demonstrated in Fig.20 and Fig.21 also indicates that bed-based system powered by ASHP could reach an ideal state for providing a cozy thermal environment for individual sleeping than conventional convection-based system under the cases with six heat transfer walls.

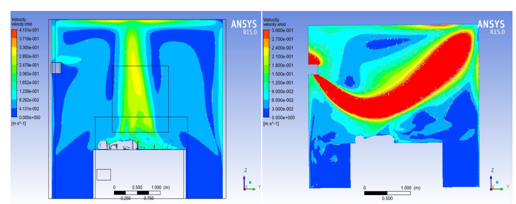
Table 9 Simulated results comparison

No covering bedding materials	AVE T in OZ	AVE V in OZ	ADPI
Bed-based system	16.29	0.073	80%
Convection-based system	14.56	0.073	4%



(a) Temperature comparison (b) Velocity comparison

Fig.12 Comparison of temperature and velocity



(a)Bed-based system (b)Convection-based system

Fig.13 Velocity contour of two systems

4. CONCLUSIONS

The following conclusions are the findings for the novel system:

The CFD simulation model has been validated by using experimental data with maximum temperature difference of 15℃(0.17%).

According to the analysis from Case study group A and B, 5mm mattress and 15mm quilt might be fairy suitable for a cozy thermal sleeping environment under experimental conditions. As the thickness of mattress and quilt decreasing, the average temperature in occupied zone increases from 5.77℃ to 15.67℃.

However, the heating performance of the new system with the same thickness of covering bedding materials under six heat transfer walls is dissatisfactory with low average temperature of 10.20℃. However, the average temperature of the novel system without covering bedding materials is 16.29 ℃ . Therefore finding the new bedding materials suitable for the novel system will be the future work.

According to the analysis of Case study group C to E, it is obvious that conventional convection-based system powered by ASHP system has poor thermal performance with significant fluctuations in airflow (more than 0.2m/s) and unsatisfied indoor air temperature (around 23℃in Case 8 and 14℃ in Case 9&10. Compared to convection-based system, bed-based system in Case study E) has better thermal performance with a high ADPI of 80% due to moderate airflow (less than 0.1m/s) as well as uniform air distribution. The air temperature of 16.29℃ under the novel bed-based system without covering bedding materials is fairly close to the ideal state of 15.8℃[13].

In conclusion, the novel bed based system powered by ASHP might be available for heating application based onthe simulation results. The thermal performance of the novel bed-based system is more uniform than conventional convection-based system. Therefore, finding suitable bedding materials to improve the sleeping environment and optimize the novel system would be the further work.

ACKNOWLEDGEMENT

The authors acknowledge the funding supports from The Hong Kong Polytechnic University for the work reported in this paper.

REFERENCE

[1] Pan D, Chan M, Xia L, Xu X, Deng S, "Performance evaluation of a novel bed-based task/ambient conditioning (TAC) system," Energy and Buildings, vol. 44, p. 54-62, 2012.

[2] Li Y, Zhuang Z, Liu J, "Chinese kangs and building energy consumption," Science Bulletin, vol. 54, no. 6, p. 992-1002, 2009.

[3] Zhuang Z, Li Y, Chen B, Guo J, "Chinese kang as a domestic heating system in rural northern China—A review," *Energy and Buildings,* vol. 41, no. 1, p. 111-119, 2009.

[4] Yongqiang X, "Study on the thermal environment of air conditon room in winter," 2004.

[5] De Swardt CA, Meyer JP, "A performance comparison between an air-source and a ground-source reversible heat pump," International Journal of Energy Research, vol. 25, no. 10, p. 899-910, 2001.

[6] Qu C, Li B, Wu H, Giesy JP, "Controlling air pollution from straw burning in China calls for efficient recycling,", 2012, ed: ACS Publications.

[7] ANSYS IC, "FLUENT user's guide," ed: Release, 2010.

[8] Mao N, "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, 2015.

[9] Gao X, Liu J, Hu R, Akashi Y, and Sumiyoshi D, "A simplified model for dynamic analysis of the indoor thermal environment of rooms with a Chinese kang," Building and Environment, vol. 111, p. 265-278, 2017.

[10] ASHRAE. Standard, "Standard 55-2013," Thermal environmental conditions for human occupancy, 2013.

[11] Lin Z, Deng S, "A study on the thermal comfort in sleeping environments in the subtropics—Measuring the total insulation values for the bedding systems commonly used in the subtropics," Building and Environment, vol. 43, no. 5, p. 905-916, 2008.

[12] Hu ZP, "Terminology standard for heating ventilation and air conditioning," HVAC, no. 6, p. 91-91, 2015.

[13] Liu Y, Song C, Wang Y, Wang D, Liu J, "Experimental study and evaluation of the thermal environment for sleeping," Building and Environment, vol. 82, p. 546-555, 2014.

[14] Room air conditioner, 2004, GB/T7725.