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Research Paper

Heat transfer characteristics of a novel sleeping bed with an integrated hot water heating system

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HIGHLIGHTS

- A novel pipe bed heating system (PBHS) is proposed.
- The thermal performance of PBHS has been obtained by experiment and simulation.
- The numerical simulation method is demonstrated to be accurate.

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ABSTRACT

This study investigates a novel and simple design for a sleeping bed with an integral hot water heating system that can satisfy the varying thermal comfort requirements of the occupants of a bedroom throughout the day. The design of heating system is presented. A mathematical model is established by analyzing the heat transfer mechanisms of the system. Experiments are conducted to determine the heat transfer of the various parts of the bed when heat source is active and inactive. Numerical simulations are performed using computational fluid dynamics (CFD) to simulate the heat transfer at various operating conditions to provide a reference for the design of the bed. The differences in the results obtained using CFD and experiments are analyzed for a selected operating condition.

1. Introduction

Each type of heating system affects the thermal environment of an interior space differently, and the types differ in efficiency. The heating system under study provides continuous and general heating of a bedroom. The design specifications for heating systems (see, for example [1]), do not account for changes in the heating zone of the bedroom throughout the day. However, several studies [2,3] have demonstrated that a desirable interior thermal environment at night differs from that during the day, so the development of a heating system that is flexible would be of great significance.

The kang, which was developed in China [4], and certain heated beds can provide desirable forms of heating. The kang is an ancient heating system that is widely used in rural residences in the colder regions of China, particularly in Nord-East China [4]. This system provides a comfortable thermal environment for sleeping because of its large thermal inertia. However, a kang does not provide adequate heating to a room during the day. Several studies [5,6] have examined the thermal performances and the comfort of the kang and have made simple improvements such as the use of two stoves. Several studies [7,8] have investigated a system that combines a kang and solar heating and found that this combined system has higher thermal performance. The use of solar energy can improve the performance and conserve energy, but solar energy systems have a very high initial cost and are complex. Moreover, the meteorological conditions in certain regions may not be suitable for solar energy systems.

Several studies have investigated heated beds. Yu et al. [9] proposed a sleeping bed that contained cylinders filled with a phase-change material. This bed acts as both a thermal storage unit and a heater, but its function is similar to that of a kang. Pan et al. [10] proposed a "task/ambient conditioning system" and demonstrated that this system could achieve significant energy savings when used in actual buildings. Neves et al. [11] proposed a blanket with an embedded controller that provides smart heating system. Wei [12] studied a new bedside device to improve the air quality of the sleep environment and tested its capacity. These beds may provide a comfortable environment for sleeping, but they are not suitable for daytime heating requirements.

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Nomenclature

a	volumetric thermal expansion coefficient (1/K)
c_p	specific heat of air (J/(kg K))
F_1	surface area of the top of the bed (m^2)
F_i	surface area of the interior surfaces of the room excluding the floor (m^2)
Gr	Grashof number
g	gravity (m/s^2)
K	temperature (°C)
l	length (m)
m	mass flow rate of air through the vents (m^3/s)
N	number of room interior surfaces
Nu	Nusselt number
Pr	Prandtl number
$q_{\lambda 1}$	conductive heat flow per unit area from the bottom bed surface to the top bed surface (W/m^2)
$q_{\lambda 2}$	conductive heat flow per unit area from the upper surface of the upper cavity to the top bed surface (W/m^2)
q_{c1}	convective heat flow per unit area between the top bed surface and the room air (W/m^2)
q_{c2}	convective heat flow per unit area between the upper surface of the upper cavity and the air temperature in the upper cavity (W/m^2)
q_{c3}	convective heat flow between a unit length of pipe and the air in the upper cavity (W/m^2)
q_{dp}	heat transferred by a unit length of pipe (W/m^2)
q_{r1}	radiative heat flow between the top bed surface per unit area and the room surfaces (W/m^2)
q_{r2}	radiative heat flow between the upper surface of the upper cavity and the other surfaces in the upper cavity except for the pipes (W/m^2)
q_{r3}	radiative heat flow between the pipe and the interior surfaces of the upper cavity (W/m^2)
q_{rw2}	radiative heat flow between the upper surface of the upper cavity and the pipes (W/m^2)
S_ϕ	source term
t	time (s)
t_0	average temperature of the surfaces of the room except the floor (K)
t_1	average temperature of the top bed surface (K)
t_2	average temperature of the upper surface of the upper cavity (K)
t_i	air temperature entering the bed (K)
t_n	room air temperature (K)
t_o	air temperature at the top bed surface (K)
U	velocity vector (m/s)
u, v, w	velocity components in the three axes (m/s)
$X_{0,1}$	shape factor between the top surface of the bed and the interior surfaces of the room

Greek symbols

ρ	density (kg/m^3)
Φ	universal variable of u, v, w, K and other variables
Γ_ϕ	generalized diffusion coefficient
λ_1	thermal conductivity of the top surface of the bed (W/m K)
δ_1	thickness of the bed surface layer (m)
α_{c1}	convective heat transfer coefficient between the top bed surface and the room air (W/m^2 K)
σ	Stefan-Boltzmann constant, $\sigma = 5.67 \times 10^8$ W/(m^2 K^4)
ε_0	emissivity of the interior surfaces of the room except the floor
ε_1	emissivity of the upper bed surface
v	kinematic viscosity (m^2/s)
Δt	temperature difference between the top bed surface and the room air (°C)

Subscripts

λ	conduction
c	convection
dp	heat transfer of the pipe
i	into the bed
n	indoor
o	out the bed
pw	pipe wall
r	radiation
rw	radiation of pipe wall
uc	upper cavity
uw	upper wall
1, 2, 3	node numbers

In typical radiant floor heating systems, pipes are embedded in a concrete slab; these are referred to as heavy systems [13,14]. Heavy radiant floor heating systems have a large thermal inertia, so the system cannot quickly switch on supplying heat between the day and night. In contrast, light floor heating systems [15] deliver heat faster because of the floor construction. Several studies [16,17] have found that radiant floor heating systems with phase change materials exhibit good thermal characteristics. Radiant floor heating systems provide heating for an entire room, while the room to be heated at night is the place around bed.

This paper proposes a novel design for a heated bed that combines the advantages of a light floor heating system, a kang and a heated bed to provide a flexible heating system for the bedroom. The proposed system includes a fan in the bed to increase the transfer of heat, and vents in the bed allow the heated air to circulate in the room during the day. Similar to a light heating system, pipes are placed in the upper cavity of the bed. The pipes heat the bed to a comfortable sleeping environment at night. Experiments and simulations were used to study the effects of the design parameters and to model the heat transfer for the design of this novel bed system.

The main objectives of this study were as follows:

- To investigate a novel heated bed design and its heating properties.
- To model the heat transfer of the bed system.
- To test the heating characteristics of the bed by experiments and simulations.
- To verify the accuracy of the numerical method by comparing the experimental and simulation results.

2. Theoretical analysis

2.1. Physical model

The layout of the bed system is shown in Fig. 1. The size of the bed is 2 m × 2 m × 0.4 m, and there is a separation board with slots that separates the interior volume of the bed into upper and lower cavities. The upper cavity is 100 mm in height, has nine air vents and contains polyethylene of raised temperature resistance (PE-RT) pipes with an outer diameter of 20 mm that circulate water. The lower cavity contains a fan, and the surface of lower