Effect of input parameters on energy requirements of phase change material integrated local heating system

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Abstract. The space heating in residential buildings in winter accounts for a considerable amount of conventional energy. Therefore, improving the performance of space heating systems with the inclusion of renewable energy sources like solar becomes crucial in order to have better occupant’s comfort while reducing energy use. Phase change material (PCM) is one of the best solutions for renewable energy, especially solar, which is intermittently available. PCM stores energy when surplus energy is available and delivers whenever it is required. It is integrated with the current system for energy storage as well as availing heat at a constant temperature. The present study will try to demonstrate the energy-saving by implementing the local heating with a spiral latent heat thermal energy storage system, when only a particular (local) space heating is of interest. In this work, an experimental as well as the numerical study of a dome over a bed was performed. Various heating coil configurations, namely floor coil, roof zig-zag, and roof spiral, were constructed to find the best configuration for the localized space heating. Experiments and simulations with the variable flow rate (0.25, 0.50, and 0.75 m/s) and varying inlet temperatures (55, 60, and 65°C) of the heat transfer fluid were carried out. It was found that the floor coil heating gives better results as compared with the other two. It was also seen that the effect of mass flow rate and inlet temperature was not that much significant after a limit. A temperature difference of 20°C was maintained between the space under consideration with the surrounding room.

1. Introduction

The buildings account for 20–40% of the total energy consumption, and its amount has been increasing at a rate of 0.5–5% per annum in developed countries [1]. As per the US Energy Information Administration 2018 report, the 2400 trillion BTU energy used for space heating, which is around 27.3% of total energy consumption in the residential sector. Luis et al. [1] did a review on building energy consumption particularly related to heating ventilation and air conditioning (HVAC) systems. They were found that out of total energy consumption HVAC accounts for 50% of building consumption and 20% of total energy consumption in the USA.

In contrast, energy savings with minimal additional cost can be achieved by smart use of energy. Behzadi et al. [2] did an experimental and numerical study to know the effect of using PCM for energy saving in residential buildings, and it was found that a substantial amount of energy could be saved by making some modifications to the existing structure. Similarly, Meng et al. [3] also did experimental as well as the numerical study of the thermal performance for PCM integrated room, and they were found that temperature fluctuation can be decreased up to 14.2°C. It was found that all these studies were focused on whole space heating. Since a lot of thermal mass (tables, chairs, books, walls, etc.) is associated with the room or space so unnecessarily require energy to reach the required temperature for the room/space. Here, in the present work, we had mostly focused on energy saving with efficient space heating, especially done by local heating systems. In today’s time, we all must think together about
energy-saving possibilities. The local heating concept is one of them, by which we can save a substantial amount of energy. The idea behind the concept is that when the small area of room/space needs to be heated, then there is no point in heating the full room/space. The inspiration for the same was taken from electric blankets used mostly in winters for warming the bed in a similar fashion, but the drawbacks with an electric blanket are many like overheating, electric shocks, dangerous cancers, electromagnetic frequencies, etc. [4]. These problems will not be associated here as we are just using the required warm water in a fully controlled manner. This work will become, base for the uses of renewable solar energy as the only source of energy has to change anytime. In order to implement solar energy, different type of active and passive heating systems [5] are already there, in which the whole space can be heated, but there is a limitation of energy storage required.

In this present work, a small attempt has been made, by which theoretically around 50% amount of energy saving can be achieved as volume to be heated was restricted to small bed surrounding instead of the heating whole room. An insulated dome was constructed over the bed with copper piping for heat transfer. The dome has proper provision for opening and closing, by a hinge joint supported with the bed. For optimum design, three different configurations (floor coil, roof zig-zag, and roof spiral) of the copper piping are considered. Both experiments, as well as numerical simulation, were done in order to optimize the energy requirement for the same. Water was used as heat transfer fluid (HTF) as it is inexpensive and readily available. So that by this technique, only the concentrated area is heated whenever it is required. In this way, not only energy saving can be done, but also environmental benefits can also be achieved. Phase change material based spiral latent heat thermal energy storage system (LHTESS) is attached with setup. Paraffin wax with a melting point of 70°C was used as PCM. As the solar energy integration was done with the PCM-based LHTESS for local heating, it provides clean and sustainable renewable solutions for these challenges [6].

2. Design and Simulation model
The experimental setup used for the local heating system (dome over the bed), along with the schematic diagram, is shown in figure 1-[A], [B], [C], [D], and [E]. Two different tanks (100L each) were used for charging and discharging, respectively. A large volume of water (100L) was used to maintain at the required temperature to avoid temperature decay during the first few cycles. An evacuated tube collector (ETC) solar water heater or an electric heater (2 kW) was used to heat the water till the required temperature. The spiral LHTESS with paraffin wax (20kg) of melting point 65°C was used as PCM to store surplus energy. The hot fluid (water) enters the dome via LHTESS through a copper pipe inlet and exits the dome through the outlet. The base of the experimental setup is made up of a plyboard with polyester cotton bedding. The roof of the setup is made with foam. The size of the bed is 6.5 ft x 3 ft. It has small openings inside walls for avoiding suffocation etc.

To start the experiment, water was heated using an ETC solar water heater or electric heater (depending upon the availability of sun), up to the required temperature (say, 70°C). The water temperature was maintained with the help of a temperature controller integrated electric heater, as the
sunlight was not available all the time. Hot water was circulated through the copper tube using an 18-Watt desert cooler pump. Heat is transferred from the heat transfer fluid to the space to keep the space in warm conditions. As the dome was insulated, the inside temperature can be maintained around 25°C while the surrounding temperature is around 10°C. Figure 2 shows the results from the experimental study with various copper tube configurations. This graph shows the temperature of the surroundings and the temperatures of the space using floor coil, zig-zag copper coil on the roof, and spiral coil on the rooftop of the dome, for the whole night, from 09:00 PM to 9:00 AM (12 hours) when the outside temperature of the room was around 10°C. It is clearly seen that floor coiled, and zig-zag coiled setups give more temperature inside the dome for the same input conditions. So, from the experimental results, it was found that the floor coil gives the best results out of all three. This could be because of the uniform distribution of energy, as these coils are spread over the whole bed; for others, the coil is mainly concentrated in the central region of the dome. So that, the floor coiled setup was explored in detail.

The simulation studies of the experiments were performed to find the temperature distribution inside the dome. This distribution will help to have the best heating configuration and for more effective utilization of energy. The geometries used for the numerical simulations for the copper coil at the bottom along with the meshing, are shown in figure 3.

Figure 3. Computational domain of dome over the bed for floor coil configuration with meshing

Figure 3(c) shows the computational domain and boundary conditions used for CFD simulations of the dome over the bed. The geometry is made in Ansys Design Modular, and Ansys Fluent 18.1 was used for simulations. The general conservation equations [7] were solved for each control volume. The dimensions and boundary conditions used for simulations are given in tables 1 and 2, respectively.

| Parameter              | Dimensions (all in cm)           |
|------------------------|----------------------------------|
| Length of bed          | 60.9 cm (1/3 of original length) |
| Width of bed           | 92 cm                            |
| Dia./ Height of dome   | 46 cm                            |
| Dia. of the coil       | 1.27 cm                          |
| Surface area of the dome | 8798 Sq. cm                     |
| Surface area of the coil | 2231 Sq. cm                     |

Table 1. Geometry specifications

| Description       | Boundary Condition | Input Conditions |
|-------------------|--------------------|-------------------|
| Hot Water Inlet   | Mass flow rate     | 338K 0.5 kg/s     |
| Hot Water Outlet  | Pressure Outlet    | - 1 Atm.         |
| Cold Air Inlet    | Mass flow rate     | 283K 0.01 kg/s    |
| Cold Air Outlet   | Pressure Outlet    | - 1 Atm.         |
| Walls             | wall               | Adiabatic         |

Table 2. Initial Boundary Conditions
3. Validation
The experimental results were used for validation. Four thermocouples were installed in the experimental setup, as shown locations in figure 4a. The temperature data were compared at the same points, and results were found in good agreement with very less error. Figure 4b shows the validation bar graph in the same points. It can be clearly seen that the simulation results are very close to the temperatures measured with experimental results. Hence, it is assumed that the equations [7] solved will provide correct results in the other studies also. Further electrical/solar energy can be replaced by any waste heat. In all the cases, the same equations are used without considering the origin of the heat transfer fluid’s energy. The temperature variation for the floor coiled setup, along with the height of the dome (yellow line in figure 4a), is shown in figure 4c. The ends of the graph are the temperature of the top (dome roof) and bottom (bed ply floor) of the setup. The decrement of temperature at the top is due to heat loss to the surrounding. The figure 4c shows that a temperature difference of 15°C can be maintained between the surroundings and the space in the dome.

4. Results and Discussion
The equations were solved for the given configuration using Ansys Fluent 18.1 for multiple cases with varying mass flow rates (0.25, 0.50, and 0.75 m/s) and hot water inlet temperature (55, 60, and 65°C) for floor coil configurations. The boundary conditions, along with the flow conditions, are shown in table 2. Figures 5a and 5b show the temperature contour for the floor coiled setup, in front and side plane, respectively, in which the average temperature inside the dome is maintained around 25°C. Figure 5c shows the velocity streamlines inside the dome. It can be seen the air movement is present throughout the domain along with good mixing of various streams. Hence, it can be assumed that the temperature of the space is uniform.

Figure 4a. Location points of thermocouples in the experimental setup  
Figure 4b. The validation bar graph in the same data points  
Figure 4c. Temperature variation along with the height (yellow line) of the dome  

Figure 5a. Temperature contour in the front plane  
Figure 5b. Temperature contour in the side plane  
Figure 5c. Velocity streamlines inside the dome

Figure 6a shows the temperature variation along with the height of the dome for all three configurations at the same inlet conditions. In the case of the spiral coil at the top, heat transfer is mainly by conduction. Hence, the highest temperature is observed near the dome. In the case of floor coil, the heat transfer is by convection. Hence, we see that the temperature of the air is more uniform near the dome. In the case of the zig-zag coil, the heat transfer takes place by both fluid conductions as well as convection because of the orientation of the coil at the roof. Hence, we see a mixed trend in the zig-zag roof coil. Figures 6b and 6c depict the effect of variation in inlet temperature and mass flow rate of the
heat transfer fluid (water). It shows the impact of the heat transfer fluid’s inlet temperature and mass flow rate for the floor coiled setup. It has a good impact on heat transfer inside the dome, but it is seen that after a certain limit, the effect of mass flow rate and inlet temperature is not that significant.

![Figure 6a. Temperature variation along with the height of the dome](image)

![Figure 6b. Effect of hot water inlet temperature variation for floor coiled setup](image)

![Figure 6c. Effect of mass flow rate variation for floor coiled setup](image)

The heat transfer is improved on the side of the heat transfer fluid due to an increase in flow rates and inlet temperatures. But the heat transfer is poor on the airsides. Hence, there are optimum values of flow rates and temperatures of the heat transfer fluids in maintaining the space at a prescribed temperature. For the optimum value of flow rates and inlet temperatures of the heat transfer fluids, further simulations are needed to be done. Also, the results of discharging with latent heat thermal energy storage system are under progress for that this study will provide valuable input. Although the concept under study is fully practical, it can also be further modified to make it more realistic by giving proper air passage and other required arrangements so that possible problems like suffocation, the heat released by humans, etc., can be addressed more appropriately.

5. Conclusions
In the current study, an attempt has been made to heat the local space. An experimental setup has been fabricated, and experiments were performed with various inlet flow conditions. Numerical simulations were performed with different configurations of the copper coil. Simulations are performed to find the temperature distribution of the space with various flow conditions. It is found that the bottom coil and zig-zag coil will maintain the space above 15 – 20°C to that of the surroundings. It is also observed that there is a limit in the mass flow rate and inlet temperature of the heat transfer fluid beyond which the improvement in conditions is minimum. The inclusion of a PCM-based thermal battery provides energy storage and delivery at constant temperature by thermal charging and discharging. This study will provide an economical and sustainable solution for required space heating. The optimum mass flow rate and inlet temperature will further increase the efficiency of the system.

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