Energy
Volume 99, 15 March 2016, Pages 250-265

A thermo-activated wall for load reduction and supplementary cooling with free to low-cost thermal water

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https://doi.org/10.1016/j.energy.2016.01.051
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Highlights

- We propose an innovative building envelope system for low-grade energy use.
- The building envelope can be easily thermo-activated with low-cost thermal water.
- The transient simulation model is developed to study the dynamics and performance.
- The system is effective in reducing thermal load and suppling energy at low-cost.

Abstract

A building envelope serves as a thermal barrier and plays an important role in determining the amount of energy used to achieve a comfortable indoor environment. Conventionally, it is constructed and treated as a passive component in a building thermal energy system. In this article, a novel, mini-tube capillary-network embedded and thermal-water activated building envelope is proposed to turn the passive component into active, therefore broaden the direct utilization of low-grade thermal energy in buildings. With this proposed approach, low-grade thermal water at a medium temperature close to the ambient environment can be potentially utilized to either counterbalance the thermal load or indirectly heat and cool the space. With the revealing of the idea, effects of water temperature and flow rate on the envelope's thermal performance are investigated using a transient model. The results indicate that the thermo-activated wall can be effective in stabilizing the internal surface temperature, offsetting the heat gain, and supplying cooling energy to the space in summer. Utilization of the innovation should take the cost of total energy, energy benefit and efficiency into consideration. This article illustrates how low-grade energy can be actively used as a means for achieving net-zero energy buildings.

Introduction

The building sector is one of the biggest non-renewable energy consumers that are not utilizing much of the renewable energy available in the nation, accounting for 41% of the total energy use in the U.S. [1]. About 50% of this energy is to thermally accommodate the internal and external thermal load and condition the indoor space. A further breakdown shows that nearly half of the load is associated with the heat gain and/or loss through a building envelope [2], [3]. In the meantime, majority of the energy currently used in buildings is obtained from the combustion of fossil fuel; this practice not only greatly impacts the energy security of our nation but also produces negative effects to the environment [4], [5]. Researches from various aspects have been conducted to reduce the excessive consumption of non-renewable energy in buildings, including, for example, improving of the theoretical efficiency of HVAC (heating ventilation and air-conditioning) equipment [6], [7] and operation efficiency of building systems [8], [9], [10], [11], and/or expanding the portion of renewable and low-grade energy sources in buildings [3], [12], [13]. Theoretically, thermal operation of buildings is indeed about the use of low-grade thermal energy. If this feature is fully utilized in the building system design and operation, a much wider horizon toward the energy and environment sustainability is open. For example, in summer, the typical indoor air temperature maintained at around 22.8 °C–26.1 °C (73 °F–79 °F) can be potentially achieved with any resources at a temperature lower than the set point. The current practice of burning fossil fuel to get electricity and then drive chillers for a thermal source at around 12 °C for cooling involves great energy quality and efficiency loss. Alternatively, developing technologies to enable low-grade energy utilization in buildings can reduce primary energy consumption, peak electrical demand and our growing dependence on non-renewable energy without necessarily lowering the desired comfort level [14], [15].

It is a fact that majority of low-grade energy existing in the nature is in the form of thermal energy or can be collected with a thermal process. Examples include the solar energy, rejected heat, shallow geothermal, etc. Despite the significant amount in general, this type of renewable energy is not suitable for long-distance transfer without conversion (e.g. into electricity). In the meantime, it can be barely adopted by conventional building mechanical systems for heating and cooling. A centralized HVAC system needs a high thermal gradient to carry the energy before it reaches the load side. In each thermal zone, energy is distributed at several locations and then diffuses toward the load side. The space is thus maintained at a dynamic equilibrium thermal condition when the distributed energy just neutralizes the load. With the analysis we can see that, inside the space, the boundary close to the external load might be the best place for the use of low-grade energy; but this opportunity has long been overlooked.

Pipe-embedded structures with water circulating inside for heating and cooling have been recently studied. The idea is to have thermo-conditioned water convey heat or coolth into the space when it is circulated through the pipes in the floor or walls. Compared to air-based systems, this approach can work with lower temperature gradients, leading to relatively easier utilization of low-grade energy sources and consuming less energy [16], [17], [18], [19]. For example, Stetiu [19] conducted research on energy and peak power saving potential of radiant cooling systems in commercial buildings in different U.S. climates. The results indicated that, when a radiant cooling system was employed instead of a traditional all-air system, average 30% of the energy consumption and 27% of the peak power demand could be saved. In order to acquire quicker heating, less loss of floor height and less floor load, a lightweight radiant floor heating system was developed. An experimental and numerical analysis was carried out on the effects of design parameters with a mathematic model constructed for a sample room [20]. The results showed that lightweight radiant floor heating had fine thermal stability and comfort. Besides direct heating and cooling by using thermal water in the structure, energy might be stored up with a pipe-embedded high-capacitance structure for load shifting. For example, a new style of radiant floor system using PCM (phase change material) was proposed [21]. The results showed nearly 18% savings on the energy consumption compared to a conventional case. Water-based radiant heating and cooling systems typically use flexible cross-lined PEX (polyethylene) pipes. Selected pipe diameters are usually in the range of 20mm–40mm with a pipe spacing between 200mm and 300mm [22]. Too big size and spacing will lead to uneven surface temperature and/or decreased occupant's comfort. Among the very few studies, Mikeska and Svendsen [23] investigated small diameter pipes integrated into the inner plate of sandwich elements made of high performance concrete. It was concluded that a sufficient amount of energy can be supplied to the space for comfort and economy by means of radiant heating and cooling systems using micro-tubes.

While aforementioned water-embedded structures appear close to our idea in form, they are fundamentally different. The main focus of those studies was around utilizing the internal structure for distributing heating and cooling. Because of this, the temperature of the circulated water has a narrow range and is not close to that of natural resources [24]. Mechanical heating and cooling is generally needed to produce the thermal water. Despite the benefits over air-based systems, this practice still excludes the potential of direct and large scale utilization of natural thermal resources. A pipe-embedded system used in a building envelope has barely been investigated. Moving pipes to the space boundary brings the thermal energy closer to the load. Therefore, it can greatly relax the constraints on the temperature of thermal sources and enable the use of close-to-free renewable energy sources. A concept along this line called TB (Thermal Barrier) using U-pipes of 26mm outer diameter was proposed for indirect heating and cooling technique driven by solar thermal radiation [25]. Polypropylene U-pipes was constructed in external walls. Fluid flows inside a U-pipes system with a variable mass flow rate and variable supply temperature to guarantee the semi-surface temperature at 17°C all year round in their study.

In summary, there has been very limited research on thermo-activated building walls with the use of low-grade thermal water in mini-tubes for load reduction and indirect heating and cooling. The impact of water temperature variation on the internal and external heat transfer and wall's thermodynamics has not been studied either. In this paper, we present a novel idea of using embedded capillary network and low-grade thermal water to change the dynamics of conventional walls and turn them from a passive component into an active one for conditioning the space. The thermal performance of the proposed wall is analyzed by using a thermal resistance circuit model. In the remaining of this context, we first introduce the background and motivation of this research. Then, we present the transient thermal model of the wall. After that, the effects of water temperature and mass flow rate inside the capillary network on the performance of multilayer wall are investigated. The energy performance of it compared with a conventional wall is also analyzed. The paper concludes with a brief discussion on the results and the future work.

Section snippets

Background and motivation

The building envelope is a key component of energy-efficient high performance buildings. In average, about 50% of the heating and cooling load comes directly through the building envelope. To reduce the thermal load through the building envelope from the ambient environment, the common practice is to add thermal mass and thermal resistance to the wall. The added thermal mass can increase the time lag and reduce the decrement factor, which are the two indexes of a building wall's thermal …

Multilayer wall with thermal capillary network

In this study, we apply the MTC thermal layer to a conventional multilayer wall. Fig.3 shows the structure of a capillary network heat exchanger and multilayer wall with capillary network. Fig.3(a) depicts that the MTC includes a group of parallel small diameter tubes. The tubes are connected to the main inlet and outlet tubes. The size and flow direction of the MTC panels can be adjusted to suit the real applications. Fast push-in fittings allow the flexible configuration of the loop. Fig.3 …

Results analysis and performance evaluation

For MTC thermo-activated walls, besides design parameters, the water temperature and the mass flow rate are two main control variables. They are varied based on the parameters given in Table3. The wall without the MTC is adopted as the base case for evaluating the performance. …

Conclusions

In this article, we proposed a novel idea of using MTC (mini-tube capillary) network with low-grade thermal water to thermo-activate conventional walls. Unlike a general water-embedded internal structure, our innovation applies the MTC at the boundary between the space and external environment and brings the thermal energy closer to the load. It can significantly relax the constraints on water temperature and facilitate the direct use of low-grade renewable energy in buildings without …

Acknowledgments

The authors gratefully acknowledge the support of this study from University of Nebraska-Lincoln Faculty Start-up Fund and Layman Award. …

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