Energy 97 (2016) 36–45

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

# Location and optimization analysis of capillary tube network embedded in active tuning building wall

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ARTICLE INFO

*Article history:*
Received 26 August 2015
Received in revised form
1 December 2015
Accepted 19 December 2015
Available online 16 January 2016

*Keywords:*
Low-grade energy
Building wall
Capillary network
Active tuning
Location optimization

ABSTRACT

In this study, a building wall with a thermal tuning function is further investigated. This design turns the building wall from a passive thermal system to an active system. A capillary tube network is installed inside the wall to manipulate the thermodynamics and realize more flexibility and potentials of the wall. This novel building wall structure performs efficiently in terms of building load reduction and supplementary heating and cooling, and the structure is convenient for applying low grade or natural energy with a wider temperature range. The capillary tube network's location inside the wall greatly impacts the thermal and energy performance of the building wall. The effects of three locations including external, middle and internal side are analyzed. The results indicate that the internal wall surface temperature can be neutralized from the ambient environment when the embedded tubes are fed with thermal water. The wall can work with a wide range of water temperature and the optimal location of the tube network is relatively constant in different modes. Power benefit with the wall changes from 2 W to 39 W when the outdoor air temperature changes, higher in summer than in winter.

## 1. Introduction

Building energy consumption accounts for 41% of the total energy in the U.S., which is one of the biggest energy consumers in the nation [1]. To reduce the primary energy consumption in buildings, researchers and practitioners have conducted numerous studies. The means can be roughly grouped into three types: 1) reducing the thermal load from the ambient environment [e.g. 2–4]; 2) improving the energy efficiency of HVAC (heating ventilation and air-conditioning) equipment and systems [e.g. 5–8]; and 3) replacing or supplementing the primary energy source with free to low-cost renewable energy [e.g. 9–11]. For example, cool roofs with high solar reflectivity and infrared emissivity were found to reduce the cooling energy demand as well as additional insulation in the west coast of the U.S. [2]. A ‘make tight, ventilate right’ approach was proposed to control the internal heat gains in office buildings in a changing climate [3]. Aerogel with different thickness in the insulation layer of a building was investigated to render the thermal load through the building [4]. Once the thermal load is formed inside the space, energy is needed to offset the load and maintain the indoor thermal comfort. Anywhere energy is used, there are potentials to increase efficiency and save energy. Optimal operation strategies, including different air-side economizer [5], set point reset [6], collaboration of air-handling units [7,8], etc. through the use of modern building automation system and control were reported cost-effective for this purpose. However, ways of optimally utilizing low-grade energy sources, such as solar energy [9], ambient cooling air [10], and geothermal energy [9,11], for building's energy savings are of equal importance.

However, renewable energy generally possesses low-grade and intermittent features if without grade-lifting or energy conversion (e.g. from heat to electricity). One of the key ideas of expanding the exergy-effective use of renewable energy in buildings is to adapt the building systems as much as possible to the features and avoid lifting of energy quality as needed in conventional HVAC systems [12]. To this end, the building structure and configuration could be considered as a part of the building system and play a significant role in linking the internal environment and the ambient environment. Among the literature, Ibrahim et al. investigated the use of closed loop water pipes embedded in building façade to utilize the solar energy gain on the surface of walls and offset the heat loss through the north wall. A simulation was conducted to evaluate the

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http://dx.doi.org/10.1016/j.energy.2015.12.094
0360-5442/

**Nomenclature**

*Abbreviations*

| | |
|---|---|
| HVAC | heating ventilation and air-conditioning |
| TAB | thermal activated building system |
| TAW | thermo-activated wall |
| RC | resistance capacitance |

*Roman letter symbols*

| | |
|---|---|
| $a$ | solar absorptivity |
| $c_p$ | constant pressure specific heat of air, J/(kg °C) |
| $d$ | thickness, m |
| $h$ | convective heat transfer coefficient, w/(m$^2$ °C) |
| $m$ | mass flow rate, kg/s |
| $A$ | area, m$^2$ |
| $C$ | heat capacity, J/°C |
| $D$ | width of wall, m |
| $H$ | head loss |
| $L$ | length, m |
| $Q$ | rate of heat transfer, w |
| $R$ | thermal resistance, °C/w |
| $T$ | temperature, °C |
| $V$ | volume, m$^3$ |
| $W$ | power, w |
| Re | Reynolds number |

*Subscripts*

| | |
|---|---|
| av | average |
| b | benefit |
| cap | capillary network |
| e | external |
| eq | equivalent |
| fr | resistance along pipe |
| j | node number |
| i | internal |
| in | inlet |
| int | internal |
| lr | local resistance |
| mor | mortar |
| o | outside |
| op | optimal |
| out | outlet |
| r | room |
| s | solar |
| sa | solar-air |
| surr | surrounding |
| tr | traditional |
| w | water |

*Greek letters*

| | |
|---|---|
| $\lambda$ | thermal conductivity, w/(m °C) |
| $\omega$ | rotational velocity |
| $\phi$ | diameter, m |
| $\rho$ | specific density, kg/m$^3$ |
| $\varepsilon$ | emissivity |
| $\sigma$ | Stefan–Boltzmann constant |

performance; an annual heating reduction between 6% and 26% was identified in different climates [13]. Zhang et al. studied the feasible use of heat pipes implanted in the wall to harvest passive solar energy for heating in winter and cooling in summer. Heat pipe can efficiently transfer heat without additional power consumption when there exist unidirectional temperature difference [14]. Lehmann et al. investigated the application range and functionality of thermally activated building systems (TABs) where the thermal mass of the building structure, mainly floors and slabs, is utilized as a thermal storage for allowing the use of renewable energy sources [15]. The water temperature used to charge the structure is close to the room air temperature. Depending on the heat gain profile, peak loads up to 50 W/m$^2$ can be provided. Because of the large thermal mass and different energy transfer characteristics, it is difficult to maintain the room air temperature in a narrow band with TABs; operation guideline and model-based predictive control of TABs coupled with air-conditioning systems were also studied by researchers [16,17].

To further relax the use of low-grade thermal water, the pipes can be embedded in the building walls rather than the internal structure. The concept of TAWs (Thermo-activated Walls) with capillary network as proposed by Yu et al. in a recent publication [12]. The idea is to maximize the benefit of using low-grade thermal water with zero or very limited lift to mitigate the thermal load through the building envelope and supplement the heating and cooling. Unlike TABs and Thermal Barrier with large pipes [18], the temperature of water fed into the tubes is not controlled. In mechanical heating or cooling season, thermal water with a temperature between the indoor air temperature and the outdoor air temperature still possesses the capability of offsetting the load through the envelope, partially or fully. It was found that the thermal water layer changes the thermodynamics and dominates the thermal performance of the wall. Energy consumption and energy benefit grow together with the decrease of water temperature applied in the capillary network in summer. In this paper, the thermal performance of a TAW due to the location of the thermos-active layer is investigated. With a temperature close to the ambient air, renewable energy or natural energy such as ground water and waste water is much easier to be utilized. In the rest of the paper, a thermal resistance circuit method is first introduced. Then, impacts of pipe location on system performance are studied, which includes the locations of external side, middle side and internal side. The optimal objective model is built for finding an optimal location of the pipe. Finally, location optimizations are performed based on a graph analysis.

## 2. Transient thermal performance analysis

### 2.1. Multilayer wall with capillary pipe network

The proposed multilayer wall embedded with capillary tube network looks apparently similar to a conventional wall. Fig. 1(a) shows the structure of pipe network heat exchanger and Fig. 1(b) illustrates the proposed multilayer wall with capillary tube network.

### 2.2. Transient thermal modeling

The heat transfer in the building wall is considered one dimension only, perpendicular to the wall surface. It can be represented by a set of thermal RC (resistance capacitance) network as shown in Fig. 2, with lumped circuits for the finite layers. Node