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Modeling of an integrated solar system

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Abstract

The feasibility of using low-cost solar collection and storage technology to provide energy for residential units is investigated. Different construction strategies were compared including traditional housing practice against newly innovative ideas such as low radiant heating system, desiccant dehumidification, integrated low-cost solar collection, and phase-change material (PCM) storage. The selected building, located in Blacksburg, VA, integrated a solar thermal roof collection system consisting of a low-temperature flat-plate collector integrated within a concrete building envelope linked to a PCM storage tank. For the considered location and weather conditions (Blacksburg, VA), the proposed collection and storage solar system can supply 88% of the building's space heating and hot water needs averaged throughout the year saving the homeowner approximately 61.5% of the annual heating bills. However, the use of a storage system is not economical for the considered conditions. The paper also shows a month-by-month demand and supply distributions for the modeled building's heating and hot water needs.

Keywords: Solar collection; Concrete construction; Integrated design; PCM

1. Introduction

Exploitation of non-renewable resources (e.g. materials, energy, etc.) can create non-sustainable conditions and environmental degradation resulting in a significant loss of final product quality. In many industrialized countries, including the US, the heating, cooling, ventilation and lighting of buildings represent approximately 40% of the annual nation's energy consumption [1]. Therefore, it is important to seek solutions that improve our quality of life, while reducing energy and environment consumption.

In the past 20 years, interest has been growing to adopt new methodologies to effectively utilize renewable sources of energy. This has yielded to a variety of possibilities and techniques with differing degrees of promise [2]. Recently, researchers have strongly promoted the use of solar energy as a viable source of energy. Solar energy possesses characteristics that make it highly attractive as a primary energy source that can be integrated into local and regional power supplies since it represents a sustainable environmentally friendly source of energy that can reduce the occupants' energy bills [3]. Although recent studies have shown that the use of solar energy is strongly supported by the US public, the cost effectiveness of this energy is still in doubt due to the current up-front costs of solar collection systems compared to traditional conventional system [4]. This has led to a certain amount of mistrust among agencies as to the true long-term benefits of these systems.

Integrating solar energy collection system into the building shell and mechanical systems may reduce the cost of the solar energy systems as well improve the efficiency of the collection. Therefore, research in building integrated solar thermal design has started in the early 1940s and is continuing today. In solar-integrated design, the building is used as part of the solar collection system. Building integrated solar thermal systems have many advantages over normal collection systems including their ability to expand to cover the entire area of the roof at a reasonable cost. These systems usually have a longer service life, which results in less replacement of materials and more conservation [5].

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In light of the aforementioned discussion, the objective of this research is to present a new methodology to integrate solar energy collection systems into the conventional building structure in order to reduce the cost of the overall system. The selected roof collector consists of a low-temperature flat-plate collector integrated within a concrete building envelope. To effectively store and use the collected solar energy based on the building energy demand, phase-change material (PCM) storage tank (crystalline, high *n*-paraffin content material with a high latent heat storage capacity) was used. The considered location for the potential construction of this system is around the campus of Virginia tech (Blacksburg, VA).

2. Mechanical system description

The building thermal loads are satisfied by the building mechanical system, which allows the building to heat, cool and ventilate itself throughout the year with the least possible dependency on non-renewable fuels. The proposed system consists of a low-cost collection system (low-cost flat-plate collector and a PCM storage tank), a dehumidification system, a low radiant heating and cooling system, a load auxiliary heating systems, thermostats, humidistats, valves and controllers. Low radiant heating and cooling systems (also known as hydronic) circulate hot or cold fluid through tubes embedded in the slabs. Energy is, therefore, either added or removed from the space. The zone occupants are conditioned by both radiation exchanges with the system, which increases their level of comfort [6].

The flat-plate collector supplies hot fluid to the moderate temperature PCM storage tank and the low radiant heating system as shown in Fig. 1. In addition, the solar collector also supplied hot fluid to regenerate the desiccant system used in the summer in the air ventilation cycle as shown in Fig. 2.

The building heating system (low radiant system) was designed to accommodate 100% of the heating loads ensuring thermal comfort conditions as defined by ASHRAE at all time [7]. The space heating and cooling loads as well as thermal comfort conditions were evaluated using Energy Plus software developed by the Department of Energy. Thermal comfort achieved by this system was measured based on the predicted mean vote index (PMV). This index predicts the mean response of a large group of people according to the ASHRAE thermal sensation scale [7]. PMV is calculated as follows:

$$PMV = [0.303\ \exp(-0.036M) + 0.028]L, \qquad (1)$$

where

M = Occupant's level of metabolic activity, and
L = Thermal load on the body.

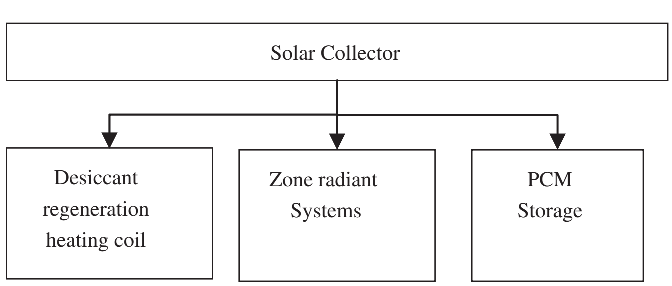

Fig. 1. Solar collector supply branches.

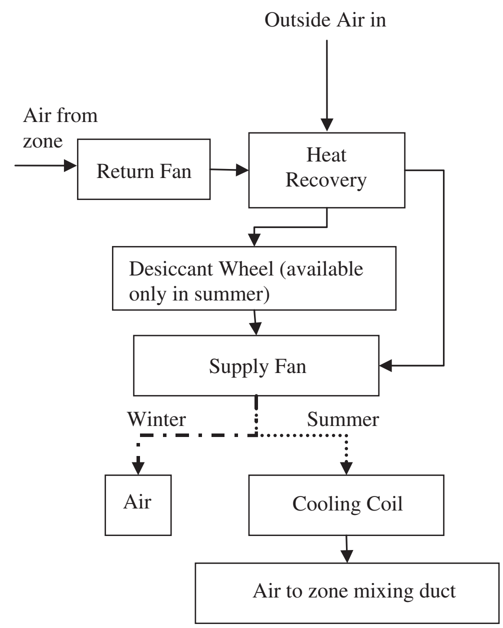

Fig. 2. Ventilation cycle.

Ventilation is accommodated using a low $\frac{2}{3}$ of the volume of the building forced air changes per minute which was equivalent to $0.76\,m^3/s$. Outside air is mixed with the zone exhaust air using a sensible heat recovery air-to-air heat exchanger. During the summer, the incoming air is passed through a desiccant wheel dehumidifier to reduce its relative humidity then passed through a water-to-air cooling coil to cool it to comfort level temperature. After that, it is transferred to the zone distribution ducts. During the winter, the desiccant dehumidification system remains idle. The air is passed from the heat recovery system to the zone distribution ducts directly through the zone supply fan as shown in Fig. 2. This ventilation cycle was designed to satisfy the comfort level within the considered location. However, other locations within the US may need dehumidification throughout the year depending upon the locations air temperature and humidity levels. All thermal zones within the simulated buildings were kept within a comfort level measured by the predicted mean vote index (PMV $\pm$0.5) as shown in Fig. 3.

3. Control strategy

The automatic control of the solar thermal system is accomplished by continuously controlling the fluid circulation pump as well as the fluid path. The fluid path is altered based on changes in system and service temperatures or changes in the level of solar radiation and ambient