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Performance evaluation of a hybrid solar heating system for farrowing houses

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ABSTRACT

An innovative hybrid solar heating system for farrowing houses was investigated in terms of energy performance. The hybrid solar system consisted of a roof solar collector, a solar mass wall, one heat storage tank, one heat supply tank and a creep heating slatted floor. The experimental period for the evaluation of the system performance had a duration of eight months; this period was to include both warm and cold periods within a year. During the warm period around 70% of the heating needs were supplied by this system, while during the cold period the achieved energy saving was approximately 25–30%. The performance of the roof solar collector was better for the creep heating than the performance of the mass solar absorber throughout the experimental period, in fact the latter contributed more to the heating of the farrowing room. It was also found, that a larger heating storage is necessary for this system in order to achieve improved performance of the excess energy produced during daylight. The results of this research will encourage the promotion of this system as a more economical and ecological for heating livestock buildings.

1. Introduction

The growing energy demands in all sectors of the economy, in addition to the increase in fossil fuels prices and the related environmental problems have created the necessity to improve energy efficiencies as well as to increase the use of alternative energy sources. The building sector has been considered as one of the major energy consumers as the building environment accounts for 20–40% of the total energy consumption [1]. Although the energy consumption of the agricultural buildings in Europe is only 2% of the total energy consumption [2], agricultural buildings were found to be among the most growing energy demanding subsectors with a projection to increase consumption by 26% by 2030 compared to 2005 [3]. It is therefore important to improve the energy efficiency of these facilities since energy consumption contributes to the cost of agricultural products.

Agricultural buildings require energy for heating, cooling, ventilation and mechanical equipment, which corresponds to about 40% of the total energy consumed for agricultural activities in general [4]. Among the most important agricultural activities with high thermal needs is the piggery industry. The comfort temperature zone for the newborn piglets is around 34–36 °C [5] at birth, which is reduced to 26 °C during weaning, while the temperature comfort zone for sows varies from 12 to 20 °C [6]. Accordingly, different amounts of heat are required for piglets and sows, respectively, while both are under the same cover and in the same pen. The most common systems used to maintain the optimum heat conditions at creeps, are heat radiation systems (infra-red heat lamps) and floor conductive heat systems (heating pads) [7,8]. The heat radiation systems have high operating costs (electricity consumption), and they are usually applied only for creep heating. Another factor is that heat lamps can potentially cause fire hazards and they cannot make direct use of solar or any other alternative energy source. On the other hand, floor heating systems can provide the comfort temperature zones for both piglets and sows, they have the ability to utilize alternative energy directly and they can be easily regulated with the use of a thermostat and generally do not have the disadvantages of the radiant heating systems. For these reasons, they have been characterized as the most convenient systems for heating in farrowing houses and the energy efficiency is high [8,9].

Usually, convectional fuels are often used for heating purposes, but their use leads to high heating costs and serious environmental distress [10]. With the improvement of the methods concerning energy shortage, renewable energy sources could be used as

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Nomenclature

ρ	density (kg m^{-3})
c	specific heat capacity (kJ kg^{-1} K)
C	thermal capacity (kJ m^{-3} h^{-1})
s	thickness (mm)
R	thermal resistance (m^2 W^{-1} K)
l	length (m)
m	mass (kg)
t_{in}	fluid income temperature (°C)
t_{out}	fluid outcome temperature (°C)
Q	heat flow (kW)
q	heat loss (kJ °C^{-1})
t_a	ambient temperature (°C)
F'	corrected fin efficiency
F	fin efficiency
F_r	heat gain factor
G	ratio between mass and the exchange surface of the pipes
U_L	overall heat transfer coefficient (W m^{-2} K^{-1})
c_p	specific heat under constant pressure (kJ kg r^{-1} K^{-1})
τ	solar transmittance
a	solar absorbance
$(\tau\alpha)$	transmittance–absorbance product
d	diameter (m)
k	thermal conductivity (W m^{-2} K^{-1})
V	volume (m^3)
$\dot{V}a$	ventilation rate (m^3 h^{-1})
I_T	solar irradiation intensity (W m^{-2})
A	surface (m^2)
W	tube pitch (m)
L	absorber coefficient affecting thermal conductivity (m^{-2})
$\dot{M}$	moisture flow (kg H_2O h^{-1})
M	moisture (kg H_2O)

a reliable substitution of conventional fuels for building heating [11]. Among the renewable energy sources that can be used, solar thermal energy is considered to be one of the most efficient and environmental friendly energy form [12].

Most studies have focused on the use of solar energy for covering heating needs in the residential building subsector (solar residential). Specifically, Mammoli et al. [13], have used a hybrid system of a flat plate vacuum tube solar collector to heat water which is channeled thereafter directly to the heating distribution system. Liang et al, [11] have studied the effect of a new solar assisted air source heat pump on the performance of a heating system. Badescu and Staicovici [14] have examined the contribution of an active solar heating system in a passive building.

Although, solar thermal energy can be considered as a potential source for heating livestock buildings, only a few studies are available in this area. Cordeau and Barrington [15] have investigated a ventilation system for a broiler barn with solar preheated air. Ozgener [16] has studied the use of a solar assisted geothermal heat pump combined with a small wind turbine for covering the heating and cooling needs of agricultural and residential buildings. Also, Wang et al. [17] have performed an economic study on the use of ground source heat pump system in Beijing and Esen and Yuksel [18] have experimentally evaluated the use of various renewable energy sources for greenhouse heating. The use of a passive solar heating system (Trombe wall) has shown considerable advantages in the Mediterranean region [19]. Martzopoulos [20] in a preliminary experimental piece of work used a solar heating system consisted of a solar collector and floor heating to cover the thermal needs of newborn piglets. The results of this work showed an energy gain of around 30% during the winter, compared to suspended infra-red heating lamps. However, the heating of farrowing houses using a solar collector combined with a solar mass wall, so as to improve the energy efficiency of the whole system, has never been reported in the literature.

In the light of the above developments, this work uses a hybrid solar system to support the heating needs of a farrowing house. The aim of this study is to investigate the performance of an innovative hybrid solar system which is able to create favorable heating conditions for both piglets and sows within a farrowing pen. In addition, this research provides valuable information towards the development of an effective hybrid heating system for livestock buildings in general.

2. Experimental setup and operation

The experiment was carried out in a well insulated prefabricated building located at the Farm of the Aristotle University of Thessaloniki (AUTH) (Fig. 1). The building is rectangular with 7.17 m length, oriented east–west and 3.67 m width. The inside height is 3.10 m. The building consists of two identical test shells (A and B); for the purpose of this study a hybrid solar system (HSS) was placed and operated in the test shell A.

The HSS consisted of a roof solar collector, a solar mass wall, a heat storage tank, a heat supply tank and a specially designed creep heating slatted floor, hereafter called a creep heating pad. These components were connected within combined system of three closed circuits: the roof solar collector circuit (A), the mass wall solar absorber circuit (B) and the heating circuit (C) for supporting the heating needs of the creep heating pad. The schematic diagram of the system used in this study is shown in Fig. 2.

The water temperature in the inlet of the heating pad was set at an appropriate temperature in order to retain the heating slatted floor (pad) at a required maximum of 36 °C. The roof solar collector and the mass wall solar absorber provided heat to the storage tank. The heat supply tank received hot water from the hot water storage tank and the heat of the supply tank was recirculated through the heating pads.

2.1. Experimental setup

A flat aluminium framed solar collector (model type: NOVASOL) was installed on the roof of the test shell (collector dimensions: 2.05 × 1.1/total area 2.255 m^2), it was insulated with 40 mm rockwool at the back and 30 mm rockwool at the sides. The fluid was a mixture of water and propylene glycol in a ratio of 4:1 weighted 1.75 kg. The inclination of the roof solar collector was 45° from October to March and 30° at the other six months.

The mass wall (heat storage) had a south orientation and was vertical to the ground (angle from the ground 90°). It consisted of a 20 cm thick, black painted concrete block. Two single glass panels 4 mm thick were installed at a distance of 17.5 cm from the black concrete block. A tubular solar absorber consisting of 40 mutually parallel copper pipes was vertically placed in the gap between the black concrete block and the glazing. The water was forced into the tubular solar absorber from the lower end to the top end of the collector via a recirculating pump. The constructive details of the mass wall are illustrated in Fig. 3. The thermal properties of the mass wall components and the calculated thermal properties of the mass wall solar absorber are given in Table 1.

The heating storage tank had a capacity of 0.2 m^3 and was equipped with two distinct tubular, spiral heat exchangers (streamers) to exchange the heat from each of the two solar collectors from the one in the roof and the other in the mass wall.